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This report results from a contract tasking Nangia Aero Research Associates as follows: The proposal is in two phases as mentioned in the above document.
The scope of the work is fairly large and a judicious choice is implied in consultation with technical monitors at AFRL.

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Energy Efficiency of Military Aircraft and Operations Surveillance, Reconnaissance, Tanker

Dr. R. K. Nangia

SUMMARY

Currently there is great emphasis on achieving efficient and optimised flight. The planned budgets and future constraints reflect this. The need for overall energy savings is being felt in all spheres of defence and commercial aviation. The military scene includes many different types of aircraft with the objectives of fulfilling many diverse roles.

Previous work was concerned with efficiency of military Jets and Turbo-Prop transport aircraft and comparisons with civil passenger and freighter aircraft. This report discusses the efficiency of surveillance, reconnaissance and tanker aircraft (both turbo-jet and turbo-prop) and Bombers.

An appreciation of Efficiency parameters leads to the consideration of speed (V), lift-drag ratio (L/D) and engine efficiency SFC with range (R), as well as operational aspects e.g. Air to Air Refuelling (AAR) and Close Formation Flying (CFF). Interplaying all these leads to new designs or morphing technologies for flight optimisation. We can think in terms of sub-systems or in a more global sense, incorporating several technologies optimally. The first stage is to identify Efficiency parameters and relate them in the military context.

Although fuel efficiency parameters work well for comparing transports, we have needed to develop additional efficiency criteria for the special purpose aircraft discussed here (e.g. stand-off distance and endurance).

The approaches will enable planners to balance fuel (and cost) efficiencies, being able to select appropriate aircraft for a given mission. This will also help in definition of future logistic requirements.

In view of the encouragement, further detailed work has been proposed in several areas.

EOARD Grant No.08-3023

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PREVIOUS REPORTS (ALSO REF.1-2)

1. NANGIA, R.K., “Energy Efficiency of Military Aircraft & Operations (Jet Transports)”, RKN/AERO/REPORT/2008-30, January 2008.

2. NANGIA, R.K., “Energy Efficiency of Military Aircraft & Operations (Turbo-prop Aircraft)”, RKN/AERO/REPORT/2008-40, July 2008.

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CONTRACTUAL DECLARATIONS

“The Contractor, Dr. R. K. Nangia,, hereby delcares that, to the best of its knowledge and belief, the technical data delivered herewith under Grant No.08-3023 is complete, accurate, and complies with all requirements of the grant.”

DATE: July 2009 Name and Title of Authorized Official: Dr R K Nangia

“I certify that there were no subject inventions to declare as defined in FAR 52.227-13, during the performance of this contract.”

DATE: July 2009 Name and Title of Authorized Official: Dr R K Nangia

CONTENTS

1. INTRODUCTION, BACKGROUND AND WORK PROGRAMME

1.1. Background & Noting of Previous Work

Several reports discussing the efficiency of Military aircraft and Operations are being prepared (See Section 2). Refs.1 and 2 were concerned with military Jets and Turbo-Prop transport aircraft and comparisons with civil passenger and freighter aircraft.

This report concerns tankers, reconnaissance and surveillance aircraft, bombers, fighter aircraft, unmanned aerial vehicles (UAV) and unmanned combat aerial vehicles (UCAV). To make it as "stand-alone" as possible we include some of the relevant content from Refs.1 and 2. The sequence has been chosen to allow a logical progression from the military transports to comparable types in the tanker and surveillance roles, both jet and turbo-prop. Comparisons between various aircraft in the tanker and surveillance roles will be relatively straightforward. However, consistent performance data for the bomber and fighter classifications is difficult to determine and comparisons will be at a low level. The fighter category encompasses a wide range of roles, from the pure interceptor fighter to the ground attack fighter-bomber. This category also encompasses front line VTOL types, carrier borne types and conventional medium range aircraft.

1.2. Introduction and Overview

Presently there is great emphasis on achieving efficient and optimised flight. Now that fuel costs are increasing, the need for overall energy savings is being felt in all spheres of defence and commercial aviation and budgets. The military scene includes many different types of aircraft with the objectives of fulfilling many diverse roles.

An appreciation of Efficiency parameters leads to the consideration of speed (V), lift-drag ratio (L/D) and engine efficiency SFC with range (R), as well as operational aspects e.g. Air to Air Refuelling (AAR) and Close Formation Flying (CFF). Interplaying all these leads to new designs or morphing technologies for flight optimisation. We can think in terms of sub-systems or in a more global sense, optimally incorporating several technologies. The first stage is to identify Efficiency parameters and relate them to the military context.

In this report we consider three categories of military aircraft, surveillance, tanker and bomber. Although consistent performance data can sometimes be "obscure", we have made several "educated" choices and with previously established efficiency metrics techniques, reasonable analyses have been shown. These can be update as improved basic data becomes available.

1.3. Content and Layout of this Report

The remainder of this report is contained in main **Sections 2 to 9**.

Section 2 refers to the scope of the work, showing the wide range of possibilities. The phased programme of work is outlined.

Section 3 refers to the Efficiency Parameters briefly. Detail has already been given in Refs.2-3.

Section 4 is an overview on Tankers, Surveillance & Bomber Aircraft (Jets & Turbo-Props).

Section 5 is on Tankers. Several US & European aircraft types are considered e.g. Boeing KC-135A and R, Airbus A310MRTT, etc.

Section 6 is on Reconnaissance and Surveillance aircraft. Several aircraft types are considered e.g. Boeing E-3, Northrop Grumman RQ-4, etc.

Section 7 is on Bombers. Several aircraft types are considered e.g. B-52H, F-111F, etc

Section 8 discusses Operational Efficiency and Range improvements.

Section 9 looks at the True Costs of STOL capability in terms of field performance.

Section 10 outlines Further Work.

Section 11 contains Concluding Remarks.

We begin with visualising the scope of the programme of work before moving on to more detailed aspects.

2. SETTING THE SCOPE OF THE PRESENT PROGRAMME (FROM REFS.1 & 2)

The overall scope of the work is broad and after discussions with the technical monitors, proposed tasks were defined and arranged in phases. These have been phased in line with funds and time estimates and are briefly outlined here.

Phase 1

We added military Jet Transport aircraft to the existing efficiency parametric data plots of civil passenger and freighter aircraft, Ref.1.

Phase 2

We introduced Turboprop aircraft to the efficiency metric databases, Ref.2.

Current Phase 3

We are including Bombers, Tankers and Reconnaissance / Surveillance aircraft into the efficiency metrics. We have also studied modifying existing metrics for specific applications as necessary.

Some Considerations to be borne in Mind in the Derivation of Efficiency Parameters for Military Aircraft

More efficient, dedicated tankers will increase the overall efficiency of operations.

Often some of the data may not always be easily available. However educated guesses and knowledge based on the physics of trends will be invaluable in deriving suitable correlations.

Often cruise phases are small for military aircraft. This will need other more representative efficiency parameters to be determined, with bias towards energy efficiency.

All these will identify areas where the efficiency gains (local or total) can be obtained.

Projected SFC improvements may be used for newer designs.

Changes in efficiency parameters occur as we begin to integrate technologies. We need to identify and understand where these are and how we can utilize them.

Some of the effects can then be used for design trade-offs and energy balances.

The possibility, type and extent of morphing in future designs needs to be considered.

Overall, the context of work will be to extend military capabilities and effectiveness but at the same time be conservative in fuel / efficiency.

2.1. Wide Range of Possibilities

Initially we consider the basic design requirements and the overall flight envelopes. A wide range of possibilities arises.

Logistics Manager / Project Designer's Viewpoint

We take the viewpoint of a Project designer towards demonstrating a new (radical) concept to fulfil performance and mission criteria throughout the flight envelope. A series of design trade studies will give an idea of how a design fulfils the demands of mission requirements (range, payload, duration against weight, cost etc.). Further, exchange rates are needed to understand the balance between the various criteria likely to be imposed.

The work programmes are aimed at giving baseline and comparative metrics. The effects and impact of introducing new design, manufacture and operating technologies can be assessed. This will pave the way towards longer-term system integration.

2.2. Phased Programme After Consultations with AFRL/VA

In Ref.1, we considered the large military transport subsonic aircraft (or low transonic). Analyses lead to comparisons with the efficiency metric work that has been conducted on civil commercial aircraft. In Ref.2, we considered the military turbo-prop transport aircraft together with comparative civil aircraft.

In this report, we consider other types of military aircraft and operations. The bombers are invariably designed and built for specific roles. It is unlikely that efficiency trends established for civil and military transports will have any significant bearing on future bomber designs. However, modes of operation may well be moderated in the light of efficiency parameters (e.g. the deployment of cruise missiles from C-5 transports has already been considered.

3. REVIEW OF EFFICIENCY METRICS, CIVIL AND MILITARY TRANSPORTS

For some years we have been engaged in independent investigations into energy and efficiency considerations of aircraft, Refs.3-11. The efficiency of military turbo-jet powered transport aircraft is discussed in Ref.1. Military turbo-prop transports are covered in Ref.2. Efficiency metrics and analysis methods discussed in detail in Ref.3 are briefly outlined here. The methods established for analysis of civil passenger jet aircraft have been progressively developed and modified to accommodate civil freighters, military transports, turbo-prop powered aircraft and, for the present report, tankers, surveillance and bomber aircraft.

3.1. Derivation of Efficiency Metrics / Parameters

We consider first, a brief summary of the weight breakdown of an aircraft, typical Payload versus Range variation and basic efficiency definitions.

Operating Empty Weight (OEW) – includes airframe and engine structure and residual fuel
Total Fuel onboard (WFT) – Block Fuel (WFB) and reserves (WFR)
Since in "normal" flight the aircraft is expected to land with fuel reserves intact one could define an "Alternative" Operating Empty Weight OEWR = OEW + WFR
Here we treat these items separately.

Maximum Take-Off Weight (MTOW) - limited by performance, strength, etc.
Take-Off Weight (TOW) – operational, less than MTOW for fatigue reduction, etc.
Payload (WP)
Maximum Payload (WPmax) - limited by volume or structural strength

$$TOW = OEW + WP + WFB + WFR$$

Nangia (Ref.3) has presented results from an appreciable data exercise on modern commercial (jet) aircraft, taking into account the distinction between Maximum Payload performance, occurring at Point A on the Payload-Range diagram, **Fig.3.1.1** and the Design Payload performance, Point D. **Fig.3.1.1(a)** compares the Payload-Range performance of the Boeing 757-200 and the much larger Boeing 747-400. The significance of mandatory fuel reserves has also been considered. Point B on the Payload-Range diagram is also of interest.

At Point B the aircraft is at maximum fuel capacity with a reduced payload whilst observing MTOW limitations. In payload terms, passenger payload is generally considered inefficient!

Passenger aircraft are designed, initially, for a particular payload over a typical commercial route, Ref.3. Civil freighters are, in general, derivatives of passenger aircraft and they will not be aligned to a specific design point.

The large military jet transport aircraft, Ref.1, have been designed and built with a specific task in mind, i.e. heavy lift, capacity for large single items of military hardware, short take-off and landing, high g manoeuvres, etc. The medium lift military turbo-prop aircraft, Ref.2, are in general developments of existing designs. Ease and economy of manufacture and capacity to carry current military cargo containers are fundamental design parameters. Combat aircraft are designed and built for specific role requirements. Surveillance, Reconnaissance and Tanker aircraft have usually been derivatives of civil transport designs.

Military transport aircraft will be called upon to operate over the entire scope of the Payload-Range envelope. However, it is noted that operation at Point A is the most efficient in terms of Payload moved and Range covered per pound of fuel consumed. For a given aircraft, range may be increased using AAR note **Fig.3.1.1(b)**. It follows that maximum fuel efficiency is achieved when operating at Point A, with AAR over long ranges.

A vast statistical database relating to civil jet aircraft design and performance has been established. Trends of aircraft component weight ratios (with respect to MTOW), OEW/MTOW, WP/MTOW, (OEW+WP)/MTOW, WFB/MTOW and WFR/MTOW have been derived, Ref.3. The results have been correlated into reliable "first-order" non-D form using aerodynamic efficiency and range parameter terms from the Breguet Range equation.

Breguet Range Equation

We use the Breguet Range cruise equation. The range R depends on the aircraft weights: at start of cruise (W1), at end of cruise (W2), and the Range parameter X. The X parameter relates the flight speed and technology levels: lift-drag ratio (L/D) and Specific Fuel Consumption (SFC). It has unit of length. This in turn leads to non-D form for range Z.

$$X = V\ L/D\ /\ SFC$$

$$R = X \log_e (W1/W2)$$

$$Z = R/X = \log_e (W1/W2)$$

$$W1 - W2 = WFC \text{ (Cruise Fuel)}$$

It is implied that W2 is given by

$$W2 = OEW \text{ (Operating Empty)} + WFR \text{ (Fuel reserves)} + WP \text{ (Payload)}$$

Fuel Reserves are dependent on range and mission but are of the order of 3 – 6% of MTOW for civil passenger aircraft.

Several approaches to define the efficiency of flight in terms of payload, range and fuel burn have been proposed. Each places emphasis on particular aspects of the flight regime or technical parameters used available. Two currently developed approaches are discussed next and a further approach based on Kuchemann's work is discussed in Section 3.3.

Approach 1, Including Take-Off and Manoeuvre Fuel

Following Green (Refs.12-13) using Torenbeek's work, to derive actual fuel burnt WFB, we need to include fuel used for take-off and manoeuvres etc, i.e. WFTM. This is of the order of 2.2% of MTOW (other values can easily be inserted).

$$WFTM = 0.022\ MTOW$$

WFB = WFC + 0.022 MTOW, WFB is the total fuel burnt

W1 = 0.978 MTOW (at start of cruise)

$X = R / \log_e (W1/W2)$ and $Z = R/X$

WFB = MTOW (1 - 0.978 exp (-Z))

The results given are slightly more general and apply for short to long ranges, bearing in mind the assumption of level of WFTM.

Approach 2, "More Global Form" for Medium to Long Ranges

Often, Payload-Range relationships exist and for sake of simplicity of analysis, we assume that W1 = MTOW. Then W2 follows from a known OEW and an assumption of WFR

W2 = OEW + WFR + WP

$X = R / \log_e (W1/W2)$ and $Z = R/X$

WFB = W1 (1 – exp(-Z))

These are then the "effective global values".

For Medium and Long ranges, the results given by the two approaches are not too different. The X values may be slightly different.

Efficiency Metrics and Non-Dimensional Forms

A measure for "useful work done" per unit of fuel used is Payload-Range Efficiency (PRE).

PRE = Payload x Range / Fuel burnt, i.e. = WP . R / WFB (in nm or km units).

Long range aircraft carry a high proportion of their MTOW as fuel (WFB + WFR) and a small proportion as payload (WP) hence PRE turns out to be much lower than on short range aircraft. The relevant non-dimensional parameters, relative to achieved technology standards are then PRE/X and Z = R/X. Where possible, this approach has been applied to tanker, surveillance and bomber aircraft.

It was noted in Refs.1-5 that, in the transport role, considerable quantities of fuel can be saved by employing a 3000 nm range aircraft with hops or with in-flight refuelling (allowing of course, in the latter case, for the fuel used by the tanker.

3.2. Extended Usage & "Ready Reckoning" Graphs

Using the Breguet Range Equation and selected weight ratio trends, several types of parametric and "ready-reckoning" graphs can be derived. Several of these were presented and discussed in Ref.3.

3.3. Küchemann Structural Constants (c1, c2) Approach

Following Küchemann, (Ref.15), Green (Refs.12-13) and Nangia (Refs.3-4), we can derive useful relationships using constants c1 & c2. These correlate well with civil passenger and freighter and military aircraft. These have been discussed in Refs.1-2.

3.4. Civil Freighters

The introductory work on efficiency of civil transport aircraft, Refs.3-4 was extended to include civil freighter aircraft (Ref.14). For illustrative purposes, data for four typical current freighters, Boeing 747-400F, 767-300F, MD-11F and the Airbus A300-600F were included in Ref.1. The weight ratio trends for the freighters showed some marked differences from the civil passenger aircraft trends, notably lower OEW/MTOW. In general, the weight ratio trends for the military jet transport aircraft, Ref.1, fitted closely to the civil freighter trends.

As an introduction to the possible trends for the current tanker, surveillance and bomber aircraft, the variations of freighter aircraft component weight ratios (with respect to MTOW), OEW, WP, OEW+WP, WFB and WFR at Pt A with Range are presented in **Fig.3.4.1**. Also shown are trends for the civil passenger aircraft, Ref.3. We note immediately that the OEW ratio trends for the freighter aircraft are near 10%TOW less than those for the civil passenger aircraft with a corresponding increase in WP ratio.

Fig.3.4.2 shows civil freighter PRE variation with Range at varying payload fractions (100%, 80%, 60% and 40% of WP_{max}). The band-widths for each payload fraction indicate scatter in the plotted data. This is partly due to variations in efficiency for freighters of varying age and design technology but may also be indicative of the accuracy of the performance data available. Similar problems have been encountered with regard to military aircraft performance data. Also shown are radial lines of constant WFB/WP. This indicates that at Pt A, the freighters are achieving a WFB/WP ratio of about 0.8. When non-dimensionalised by Z, the trends of **Fig.3.4.2** take on a different emphasis, **Fig.3.4.3**. Here, PRE/X for a given payload fraction remains almost constant as Z varies. Also included in **Fig.3.4.3** is the Pt A PRE/X – Z trend for the civil passenger aircraft indicating the greater efficiency of the freighter aircraft at all payload fractions.

Fig.3.4.4 shows the civil freighter PRE/X trends with Z from **Fig.3.4.3** superimposed onto Civil aircraft trends. We note that civil freighter operation at Pt A equates closely to the c1+WFR = 0.30 and c2 = 1.6 trend (See Ref.3 for c1 and c2 usage).

These trends may be compared with those derived for tanker, surveillance and bomber aircraft in the appropriate sections.

3.5. Adaptation to Military Aircraft

The approach and principles outlined here allow adaptation to all sorts of situations in the local or overall sense (alluding to Exergy) with reference to Logistics and Mobility considerations. In military aircraft operations, depending on the mission envisaged, the OEW, WP and WFB are likely to be different from the corresponding parameters for commercial aircraft and this will imply different quantitative results from those in Ref.3. It is however, appreciated that military needs and objectives are often very different i.e. effectiveness, stealth, manoeuvrability, etc. are required without a dominant concern for fuel usage or costs over a desired time frame.

We also need to consider other issues e.g.

- Acknowledge that some military transports have been adapted from the civil scene (except in the case of the heavy lifters)

- Traditionally, military aircraft are designed to specific roles – fighter, bomber, reconnaissance, land-based / carrier-based. Currently, with significant awareness of costs, multi-role designs with options for different operating scenarios are becoming the norm.

- Modern materials and controls will allow morphing structures to expand the flight envelopes of future designs, adaptive intakes, morphing wings (design optimised for T/O, cruise, Landing, etc.)

3.6. Turbo-prop and Jet Engine Thrust Comparisons

For the turbo-fan powered civil passenger and freight aircraft and the military transports considered in Ref.1, Thrust to Weight ratios (T/W) were fairly easily defined. For turbo-fan engines, currently in service, the thrust is conventionally quoted as the maximum static thrust at Sea Level, Ref.17.

The turbo-prop configuration derives its thrust from both the gas turbine driven propeller and the exhaust gases. Turbo-prop engine power is usually given in Equivalent Shaft Horse Power (ESHP), Ref.16, where the exhaust gas thrust component is converted into Shaft Horse Power (SHP) and added to the SHP delivered to the propeller.

For initial direct T/W comparisons between turbo-fan and turbo-prop aircraft we have used a simple conversion, Ref.16, to define the turbo-prop effective thrust, T_e (lb) = 2.5 x ESHP.

3.7. Take-Off and Landing Field Length Considerations

Typical trends for MTOW against Take-Off Field Length were established for civil passenger and freighter jet aircraft and presented in Ref.3. Taking into account the variation in technology encompassed, (early 1950s to current designs, two, three and four engined aircraft, etc.) the trends were quite well defined. The trends were reproduced in Ref.1 together with data for the military heavy transport jet aircraft. Data for military and civil turbo-prop aircraft have been added. The civil and military turbo-prop aircraft lie close to the trend for the civil jets. The Airbus A400M has similar take-off performance to the very large military jet transports.

The established civil aircraft Take-Off performance trends allow comparison of Take-Off trends for the military aircraft. Reliable data for the latter are rather sparse. In a few cases, full Take-Off distance v TOW at varying altitude and atmospheric conditions are available. In general, either single point information is given or none at all. The available data have been used to establish variations in Take-Off Field length requirement with tanker offloads.

4. TANKER, SURVEILLANCE & BOMBER AIRCRAFT, JET & TURBO-PROP

Performance data have been obtained from a wide variety of sources, Refs.17-48. Naturally, there can be significant variations in data given. This depends largely upon the nature of the source, e.g. historical (text books), commercial (sales), political (governmental procurement). Tanker, Surveillance and Bomber aircraft to be assessed, were initially selected from those currently in service, Ref.17.

A large proportion of tanker and surveillance aircraft have been derived from, or in parallel with, civil airliners. A significant amount of background data has been obtained from text books (Refs.18-22). Further general data have been obtained from websites (Refs.23-31). Some detailed information related to specific aircraft types is available in manufacturers' pocket guides (Refs.32-38). Many weekly and monthly periodicals have provided additional, confirmatory information (Refs.39-48).

We take a brief overview of the Tanker, Surveillance and Bomber classifications.

4.1. Tanker & Surveillance Aircraft, General Overview

It is interesting to note that a significant proportion of large jet tankers and large jet surveillance aircraft are derived from the Boeing 707. Similarly the Lockheed C-130 has provided the basic airframe for many turbo-prop tanker and reconnaissance derivatives.

We categorise these types of aircraft as follows

(1) Jet powered (2) Turbo-prop powered

Each category may be subdivided into large, medium and small, based on MTOW.

Large	MTOW greater than 300,000 lb
Medium	MTOW 100,000 lb to 300,000 lb
Small	MTOW less than 100,000 lb

The small aircraft category can be further subdivided into manned and un-manned. The following table gives typical examples of aircraft types and classification.

CATEGORY		JET		TURBO-PROP	
		Aircraft	**MTOW**	**Aircraft**	**MTOW**
TANKERS	Large	KC-135	322500	A400M	300900
	Medium			C-130	155000
SURVEILLANCE & RECONNAISSANCE	Large	E-3	354000		
	Medium	737 AEW&C	171000	EC-130	155000
	Small (M)	U-2	40000	E-2A	54426
	Small (Un-M)	Global Hawk	32500	Predator B	10500

With the exception of very particular AAR "buddy-buddy" operations there are no medium or small jet tankers. Similarly there are no small turbo-prop tankers. The large jet surveillance category is dominated by Boeing 707 and 747 derivatives. There are no large "Western" turbo-prop surveillance aircraft. It is interesting to note that the manned U-2 and the un-manned Global Hawk have similar MTOW and perform similar tasks at similar altitudes (60,000 – 70,000 ft).

In this study we will focus on efficiency aspects of the large jet tankers, large and medium turbo-prop tankers, large jet and medium jet and turbo-prop surveillance aircraft. We will have a brief look at the small, jet and turbo-prop, manned and unmanned surveillance aircraft.

In the case of tankers, the definition of payload (WP) in terms of available fuel for offload is easily estimated since MTOW and OEW are clearly defined. For surveillance aircraft with operators in addition to the flight crew and a significant amount of electronic hardware integrated into the airframe, OEW and hence WP, are not clearly defined. These points are discussed in Section 6.

Fig.4.1.1 gives a broad overview of the B707 tanker and surveillance derivatives in silhouette form. The E-6B is shown in **Fig.4.1.2**. Boeing have offered the B737-200 airframe for development as the 737 AEW&C, **Fig.4.1.3**. The E-4 is derived from the B747, **Fig.4.1.4**. **Fig.4.1.5** shows the B767 surveillance derivative (E-767). The Lockheed U-2 reconnaissance aircraft is shown in silhouette in **Fig.4.1.6**. The Un-manned Northrop Grumman RQ-4A and RQ-4B/N Global Hawk surveillance aircraft are shown in **Fig.4.1.7**.

The two turbo-prop tanker derivatives considered are the Lockheed C-130J, **Fig.4.1.8** and the Airbus A400M, **Fig.4.1.9**.

4.2. Bomber Aircraft, General Overview

The design and performance of the large strategic bombers varies significantly depending upon their initial design role. In Section 7 we look at the performance of three current "heavy" bombers, the Rockwell B-1B, Boeing B-52 and the Northrop Grumman B-2A. Where appropriate, details of Soviet counterparts are noted. We also compare the performance of the F-111.

4.3. Sizing & General Parameters

Fig.4.3.1 shows the relationship of subsonic L/D max with normalised span in terms of wetted area. See Refs.1-2 for further discussion.

5. TANKERS

We consider both jet and turbo-prop tankers. Tankers may operate as air-to-air refuellers or as ferry tankers to deliver fuel to "outstation airfields". As air-to-air refuellers, they may operate in a variety of modes. Two extreme cases are-

to rendezvous with an aircraft, e.g. transport or bomber, requiring additional fuel to complete its non-stop, long-range mission or

to remain "on station" for lengthy periods to provide additional fuel to surveillance or combat aircraft as and when needed.

Refuelling operations are, in the main, carried out at medium altitude (~ 25,000 ft) at reduced speed. There may be a requirement for low (e.g. helicopters) and high altitude operations. There is a requirement for low speed operations when refuelling helicopters, usually carried out by turbo-prop aircraft.

We consider as wide a range of tankers as possible. Some have recently retired from service others are proposals for future tanker replacements.

5.1 Analysis Method

For a preliminary assessment of Tanker efficiency we use a modified version of the Breguet Equation analysis discussed in Section 3. A typical tanker Mission is shown in schematic form in **Fig.5.1.1**. The operational refuelling speed is defined as V_{AAR}. Time "On Station" (TOS) is measured in hours. The "On Station" sector is flown at V_{AAR}. The On Station Range (ROS) is given by TOS x V_{AAR}. At Take-Off the tanker weight is TOW. In general, this is near or at MTOW. Fuel equivalent to 2.2% of TOW is consumed from Take-Off to start of cruise, at which point the tanker weight is W1.

We define the tanker weight at various points in the mission as follows:

Take-Off	TOW		
Start of Cruise	W1	= 0.978 x TOW	
Operational Radius	W2	$= W1/e^Z$	where Z = Radius / X
End of "On Station" sector	W3	$= W2/e^Z$	where Z = TOS x V_{AAR} / X
Start of Return Leg	W5	= W6 x W1/W2	
Landing	W6	= OEW + Reserves	

Initially, the fuel available for transfer is W3 – W5. However, some fuel will be consumed by the tanker during transfer. This will depend upon the fuel transfer rate. An iterative process is employed to equate fuel available to fuel transferred and fuel consumed.

This offers a very general assessment of the tanker fuel consumption. Reasonable correlation is achieved against published offload / radius of operation / time on station data for the A310 MRTT. It affords a consistent comparison method for all the tankers studied. Several refinements to the method can be envisaged.

An additional efficiency parameter, comparable to Payload Range Efficiency (PRE) for civil transport aircraft, is defined for tankers. In this case the "useful" payload is only carried to the refueling point and the tanker will return to base with only return range fuel and reserves onboard. Tanker Payload Range Efficiency (TPRE) is given by:

TPRE = Offload x Radius of Operation / Total Fuel consumed by tanker

A similar metric is defined for the bombers in Section 7.

Aircraft developed and designed for tanker operations frequently have a dual role as transport aircraft. In this study we are mainly concerned with their tanker role although dual role capabilities will be noted. The jet tanker aircraft considered in this section are A310 MRTT, A330 MRTT, KC-10A, KC-135A-R, KC-767 and KC-30. The turbo-prop tankers considered include A400M and KC-130F/R/T/J.

The KC-767 has a maximum payload capacity of 55% of its civil counterpart (B-767-300F). The KC-767 has a slightly lower MTOW and has only 80% range capability at an equivalent payload. These characteristics are broadly indicative of the penalties introduced by dual role requirements.

Fairly comprehensive estimates are available for the A400M AAR envelope. These are shown in **Fig.5.1.2**. Also shown are the rather limited number of "corner points" available for the other tankers considered. On this basis we have limited our initial comparative analysis of tanker efficiency to 300 kt refuelling speed for the jet / turbo-jet tankers and 200 kt for the turbo-prop tankers. We have not, yet, assessed the effects of altitude.

We assume fuel reserves equal to 5% MTOW and offload fuel transfer rates between 2000 and 8000 lb/min. Current boom technology affords transfer rates of about 8000 lb/min. Hose and Drogue transfer rates are 2000 – 2500 lb/min.

When operating as tankers, the total fuel onboard can be distributed as required between payload fuel, block fuel and reserve fuel. The payload – range diagram for each aircraft assumes a modified version of that shown in **Fig.3.1.1**. The addition of fuselage tanks allows the fuel capacity limit line (Pt.B/D to Ferry point) to move to the right on the payload – range diagram. The MTOW limit line (Pt.A to Pt.B) can be extended to larger effective payloads at correspondingly reduced ranges. To establish a comparative tanker component weight ratio (with respect to MTOW) diagram, we have selected a fuel payload of 100,000 lb and determined the range over which this could be transported by each tanker. The results are shown in **Fig.5.1.3**. The largest tanker considered is the KC-10A which can transport 100,000 lb fuel over 6170 nm. The smallest, oldest and least efficient tanker is the KC-135A which can transport 100,000 lb fuel over 2490 nm. The re-engined KC-135R has a 50% range improvement. Surprisingly the A310MRTT and the KC-767 with this payload have similar ranges to the KC-135A. However, their block fuel requirements are 40% less than the KC-135A. We shall make further efficiency comparisons in the following sections.

The variation of Thrust to Weight ratio (T/W) with maximum payload range for the tankers is shown in **Fig.5.1.4**. We note that the KC-135A is under-powered in comparison to modern civil and military transports. To augment thrust at maximum performance take-off, the KC-135A used water injection (5000 lb for approximately two minutes). The re-engined KC-135R (50% thrust increase) is compatible with the more modern airframes.

The variation of MTOW with Take-Off distance is shown in **Fig.5.1.5**. The trends for civil and military transports are also shown. The definition of Take-Off distance quoted in the various sources is not consistent (Take-Off roll, distance to 35ft obstacle or distance to 50ft obstacle). Allowances have been made for obvious variations. In general, the tankers follow the civil transport trend. The A310MRTT, despite its high T/W ratio, appears to have relatively poor take-off performance, comparable to that of the under-powered KC-135A. These trends are again borne out in **Fig.5.1.6**, variation of T/W with Take-Off distance.

The A330MRTT, with a more modern wing with high lift devices, requires 10% less Take-Off distance than the KC-10A or KC-135R. The KC-135R, although having 50% better T/W ratio than the KC-135A, still requires a similar Take-Off distance to its predecessor. Both aircraft have relatively basic wing design (minimal high lift devices).

The variation of wing span (b ft) with MTOW for the tanker aircraft is shown in **Fig.5.1.7**, together with trends for the civil and military transports. The tankers are derivatives of civil or military transports and their data lie well within the established trends. The three-engined KC-10A lies slightly below the trends and the KC-130 turbo-prop lies above the trends. The large turbo-prop A400M is close to the KC-135A and R.

5.2. A310 MRTT

Conversion of the Airbus A310 civil airliner to A310 MRTT is carried out by Airbus Deutschland / Lufthansa Technik. The A310 MRTT is offered as a smaller, more affordable competitor to EADS's Airbus A330 and Boeing's 767 tanker.

The A310 MRTT is powered by two GE CF6-80C2 turbo-fans with 53,500 to 59,000 lb st thrust each. In its transport configuration it can carry 88100 lb of cargo. Payload – Range performance for the civil and military versions are compared in **Fig.5.2.1**, Ref.32. We note that the military version has 30,000 lb greater MTOW and almost 30% more range with a payload of 75,300 lb. The OEW/MTOW ratios are 0.489 and 0.531 for the military and civil versions respectively, implying a greater fuel fraction for the military version. This is confirmed by the lower Range parameter evaluated, i.e. 13150 nm compared to 14100 nm for the civil aircraft. This apparent reduction in efficiency may be attributed to several factors, increased OEW due floor strengthening and additional equipment (five centre fuel tanks, pumps, hoses, combat countermeasures, etc.), the presence of the refuelling boom and wing refuelling pods, etc.

A fairly broad scope of performance data is readily available for the A310 MRTT. This tanker has been analysed in detail and results correlate well with the published data. The methods established have then been used to evaluate other tankers.

The table below shows typical data available for the type.

	MTOW	**TOW**	**OEW**	**WFT**	**WP**	**Range**
Transport	361554	361554	176705	85943	75350	3915
Tanker	361554	359457	176705	182752		

The published variation in Fuel Offload with Radius of operation and "time on station" is shown in **Fig.5.2.2**. This figure also shows predicted results for comparison. The manufacturers estimate of 50 tonnes fuel transferable at 500 nm with two hours on station appears to fall below the quantity available as shown in **Fig.5.2.2**. This apparent discrepancy may be due to altitude and speed variations. **Fig.5.2.3** shows predicted offloads at larger radii of operation for direct comparison with the other tankers analysed (TOS = 0). Fuel transfer rate is 8000 lb/min. Also shown, for comparison, is the payload-range diagram for the transport aircraft with range halved to give an equivalent radius of operation. At 3000 nm radius of operation, the tanker can offload 31754 lb of fuel and then return to base in "ferry mode" (zero payload), a total of 6170 nm flown.

The predicted offload, radius, TOS carpet is shown in **Fig.5.2.4** for fuel transfer rate of 8000 lb/min via the boom (solid lines, dashed lines are for 2000 lb/min, single hose and drogue). A lower transfer rate implies that the tanker is offloading over a longer period and therefore consuming more fuel thus reducing the quantity available for transfer.

The following table shows total fuel breakdown (offload, block, reserves) for the tanker during typical operations (with boom, 8000 lb/min). These correspond to particular points in **Fig.5.2.4**.

Op rad (nm)	TOS (hr)	WFT (lb)	WFB Out (lb)	WFB On-Stn (lb)	Offload (lb)	WFB Offload (lb)	WFB Return (lb)	Res (lb)
400	8	182752	18441	56889	82538	790	6016	18078
400	0	182752	18441	0	138887	1331	6016	18078
2000	8	182752	57508	50372	24533	265	31996	18078
2000	0	182752	57508	0	74366	804	31996	18078

From the above breakdown we make some interesting comparisons. For each operation, the aircraft is fuelled to its maximum capacity (182752 lb) and takes-off at 359457 lb. Fuel reserves of 5% of MTOW are constant at 18078 lb. Returning "empty" over 2000 nm rather than 400 nm requires five times as much fuel. Flying out to 400 nm rather than 2000 nm requires 68% less fuel. At 400 nm radius, the tanker can immediately offload 138887 lb fuel, taking 18 minutes at 8000 lb/min (boom), consuming 1331 lb fuel itself. If the tanker were to loiter for 8 hrs at this radius it would consume 56889 lb fuel and then have only 82538 lb fuel available for offload. This would take 10 minutes at 8000 lb/min and consume 790 lb fuel.

Fuel Offload is plotted against Offload/WFB_{tot} in **Fig.5.2.5** for the various types of operation (radius 400 nm to 2000 nm and TOS 0 to 8 hr) shown in **Fig.5.2.4**. WFB_{tot} is the total fuel burnt by the tanker from take-off to landing. Offload/WFB_{tot} is an efficiency parameter, e.g. "pounds of fuel offloaded per pound of fuel consumed". We note that the efficiency parameters for all operations in **Fig.5.2.4** lie on a smooth curve. This will be compared with other tanker performance in Section 5.9. Naturally it is most fuel efficient to operate the tanker at the shortest range from base possible with minimum time spent on station. From **Fig.5.2.4**, we can see that an Offload of 100,000 lb can be given at a variety of ways. These are tabulated as follows.

Radius(nm)	**Time on Station (hr)**
400	4.86
563	4.0
800	2.62
900	2.0
1200	0.37
1275	0.0

The Offload/WFB_{tot} ratio is 1.57. For this aircraft, no matter how the 100,000 lb fuel is delivered, 63,700 lb fuel will be consumed by the tanker.

The variation of fuel offload available with deployment range (delivery of fuel to an "outstation airfield") is shown in **Fig.5.2.6**. The theory agrees closely with the published data at 2000 nm and 4000 nm range.

Take-Off performance in terms of Offload Fuel available versus field length is in **Fig.5.2.7**. We make Take-Off performance comparisons for the tankers analysed in Section 5.9.

5.3. KC-135A and KC-135R

The Boeing C-135 Stratotanker family of aircraft were initially developed alongside the civil Boeing 707. The KC-135A is a tanker that can carry up to 83000 lb of cargo without reconfiguring. Continually developed, the latest variant (KC-135R) has 50% better offload at 2000 nm than the KC-135A. The early KC-135As were powered by four J57-P-59W turbo-jet engines with 13,750 lb st thrust each. The requirement for water injection to augment thrust at maximum performance take-off was noted in Section 5.1. The KC-135R is powered by

F108-CF-100 turbo-fans with 22,000 lb st thrust each, an increase of 60%. The table below shows typical data available for each type.

	MTOW	TOW	OEW	WFT	Offload	Radius
KC-135A	316000	309600	106307	203293	120000	1000
					24000	3000
					0	4000
KC-135R	322500	322500	119212	203288		

Using available published data, theory gave a low X value of 8000 nm for the KC-135A. However, this gave very good correlation with the published data for offloads at various ranges. The modern turbo-fan engines fitted to the KC-135R with 60% higher thrust, give a proportionate increase in X, approaching 13,000 nm. The corresponding off-load at 2000 nm radius for the KC-135R is 47% greater than for the KC-135A, which agrees well with the published claims. The variation in Fuel Offload with Radius of operation is shown in **Fig.5.3.1** for the KC-135A. Fuel transfer rate is 8000 lb/min. Also shown are the published data for the KC-135A.

The predicted offload, radius, TOS carpet for the KC-135A is shown in **Fig.5.3.2** and Fuel Offload is plotted against Offload/WFB_{tot} in **Fig.5.3.3**. We note that the efficiency parameters for all operations shown in **Fig.5.3.2** lie on a smooth curve in **Fig.5.3.3**. This will be compared with other tanker performance in Section 5.9. Published data suggests that the KC-135A can offload 120,000 lb at 1000 nm radius. This point is shown in **Fig.5.3.2**. It lies below the TOS = 0 hr theory line indicating that about 30 min has been allowed in the published data for “rendezvous, hook-up and detach”.

The variation in Fuel Offload with Radius of operation is shown in **Fig.5.3.4** for the KC-135R (8000 lb/min). The predicted offload carpet for the KC-135R is shown in **Fig.5.3.5** and Fuel Offload is plotted against Offload/WFB_{tot} in **Fig.5.3.6**. Again, we note that the efficiency parameters lie on a smooth curve in **Fig.5.3.5**. This will be compared with other tanker performance in Section 5.9. Published data indicates that the KC-135R has a 50% greater offload capability at 2000 nm than the KC-135A. Assuming a 30 minute allowance for “hook-up” the theory indicates a 47% increase in offload for the KC-135R.

5.4. KC-10A Extender

The Boeing KC-10A Extender is a derivative of the McDonnell Douglas DC-10. In its transport configuration it can carry over 169000 lb of cargo. The Extender is powered by three GE CF6-50C2 turbo-fans with 52,500 lb st thrust each. The table below shows typical data available for the type.

	MTOW	TOW	OEW	WFT	WP	Range
Transport	590000		244630	238236	169409	3800
					100000	6000
					0	10000
Tanker	590000	590000	240065	238236 wing tanks		
				117829 bladder tanks		
				356065 total capacity		
	590000	590000	240065	349935 total at T/O		

Our analysis methods gave an X value of 13848 for the KC-10A Extender in its transport role. This value was used to estimate the tanker fuel offloads at various ranges. The variation in Fuel Offload with Radius of operation is shown in **Fig.5.4.1**. Fuel transfer rate is 8000 lb/min. Also shown, for comparison, is the payload-range diagram for the transport aircraft with range halved to give an equivalent radius of operation. On station at 3000 nm, the tanker can offload 123,300 lb of fuel and then return to base in "ferry mode" (zero payload), a total of 6230 nm flown. The transporter can carry 100,000 lb of payload for 6000 nm.

The predicted offload carpet for the KC-10A is shown in **Fig.5.4.2** and Fuel Offload is plotted against Offload/WFB_{tot} in **Fig.5.4.3**. We note that the efficiency parameters for all operations shown in **Fig.5.4.2** lie on a smooth curve in **Fig.5.4.3**. This will be compared with other tanker performance in Section 5.9. Published data, Ref.41, suggests that the KC-10A can offload 200,000 lb at 1910 nm radius. This point is shown in **Fig.5.4.2**. It lies close to the TOS = 0 hr theory line.

5.5. A330 MRTT and KC-30

The Airbus A330-200 was proposed for development for two tanker / transport aircraft, the A330 MRTT (Multi-Role Tanker Transport) by Airbus / EADS and the KC-30 by EADS / Northrop Grumman. Both development teams offered similar engines, the CF6-80E1 or PW4168A. Airbus also offers the Trent 772B. The specifications differ slightly between the two tankers. In the following table we show current data published in Ref.17 and earlier data given in manufacturers' handbooks.

	Ref.17 **A330MRTT**	Ref.17 **KC-30**	Ref.33 **A330MRTT**	Ref.35 **KC-30**
MTOW	515650	513700	513700	
OEW	274515	301250		
Span (b, ft)	197.1	197.8	197.1	197.8
Length (l, ft)	193.7	192.9	193.6	192.9
Wing Area (S, ft^2)	3893			
WFT	242100	246230	245300	245000
WPA	136687		136687	

A brief assimilation and analysis of the above data together with data obtained from published literature gives the following:

	MTOW	TOW	OEW	WFT	WP	Range
A330 MRTT Transport						
	513700		265657		136687	4200 Pt A
					110231	5300
					Ferry	9400
A330 MRTT Tanker						
	513700		265657	248043	(6.75 lb/USgal)	

The slight differences in OEW, WFT and MTOW that arise in the KC-30 data may be due to different engines, cabin furnishings and fuel transfer equipment specifications. When verified, these will be worth further analysis. In the troop transport configuration the A330 MRTT specification is very similar to the A330-200 civil airliner. The A330 MRTT can refuel from two wing pods at 2800 lb/min each, a centreline unit at 4000 lb/min or a boom at 8000 lb/min. Developed boom units may offer up to 10,000 lb/min.

The variation in Fuel Offload with Radius of operation is shown in **Fig.5.5.1**, fuel transfer rate of 5600 lb/min, together with effective payload – radius data for the original Airbus A330-200. The predicted offload carpet for the A330 MRTT is shown in **Fig.5.5.2** and Fuel Offload is plotted against Offload/WFB_{tot} in **Fig.5.5.3**. We note that the efficiency parameters for all operations shown in **Fig.5.5.2** lie on a smooth curve in **Fig.5.5.3**. This will be compared with other tanker performance in Section 5.9. Published data, Ref.33, suggests that the A330 MRTT can make 132,300 lb available on station for 6 hrs at 400 nm radius. This point is shown in **Fig.5.5.2**. It lies close to the predicted line.

5.6. KC-767 Tanker Transport

The Boeing 767 Tanker Transport is based on the civil B767-200ER. It is equipped with two wing refuelling pods, each capable of delivering 2670 lb/min, a centreline hose unit (4000 lb/min) and a boom (6000 lb/min). Manufacturers preliminary performance data are shown in **Fig.5.6.1**, Ref.36. From the payload – range diagram for the transport variant the following data have been derived.

	MTOW	TOW	OEW	WFT	WP	Range
KC-767 Transport						
	395000		192000		68000	4625 Pt A
					40000	6000
					Ferry	8100
KC-767 Tanker						
	395000	384826	192000	192826	(6.70 lb/USgal)	

The derived Payload – Range diagram with PRE isobars for the B767-200ER from Ref.3 is shown in **Fig.5.6.2**.

Assuming fuel reserves of 5% of MTOW at Point B, we estimate X to be 14000. The variation in Fuel Offload with Radius of operation is shown in **Fig.5.6.3**. Fuel transfer rate is 8000 lb/min. Also shown in this figure are the manufacturer's predicted performance for the 767 tanker and 767 transport aircraft, published in 2002, Ref.36. These vary slightly from current performance estimates. The predicted offload carpet for the KC-767 is shown in **Fig.5.6.4** and Fuel Offload is plotted against Offload/WFB_{tot} in **Fig.5.6.5**. We note that the efficiency parameters for all operations shown in **Fig.5.6.4** lie on a smooth curve in **Fig.5.6.5**. This will be compared with other tanker performance in Section 5.9.

5.7. KC-130 Tanker Transport

The Lockheed C-130 Hercules turbo-prop transport aircraft, **Fig.5.7.1**, has been detailed in Ref.2. As the C-130 has developed, several variants were converted to tanker operations. Early types are designated KC-130F, -130R and –130T, the most recent being the KC-130J.

Precise data for the Hercules tankers have been difficult to define. MTOW is usually given as 175,000 lb without g rating being specified. For the C-130J transport MTOW at 2.50g and 2.25g was 164,000 and 175,000 lb respectively. The published payload – range diagram for the C-130J is shown in **Fig.5.7.2** and field performance data are shown in **Fig.5.7.3**. The derived payload – range diagram, with PRE isobars, for the C-130J at 2.25g (reserves equal to 4% MTOW), from Ref.2, is shown in **Fig.5.7.4**. Also shown is the outer envelope for 2.50g operation together with a payload – range point for the KC-130R/T. The implication is that the data for the KC-130 transport is given for 2.25g operation.

The variation in predicted Fuel Offload with Radius of operation is in **Fig.5.7.5**. Fuel transfer rate is 4000 lb/min (two hose and drogue). The C-130J payload – range envelope (2.50g, noting the limitation imposed by wing relief fuel retention on landing) is repeated in **Fig.5.7.5** as payload versus radius range, together with an offload versus radius of operation point for the KC-130 tanker. The implication here is that the tanker data is given for 2.5g operation.

	MTOW	TOW	OEW	WFT	WP	Range
Transport	175000	164000	833000	86320	38258	2875

	MTOW	TOW	OEW	WFT
Tanker	175000	164000	833000	86320

For the KC-130, we have used an X value of 12743 nm as derived in Ref.2 for the C-130J. Assuming reserves of 4% MTOW we predict a range of 2863 nm for a payload of 38358 lb. This compares well with the published data.

We then use this efficiency parameter to reproduce the Fuel Offload – Deployment Radius characteristic. We have assumed a fuel transfer rate of 4,000 lb fuel per minute and 200 kt during transfer. Fuel transfer rates of 2040 lb per minute per pod are quoted for the KC-130J. The resulting Fuel Offload – Deployment Radius diagram is shown in **Fig.5.7.5**. The predicted offload, radius, TOS carpet is shown in **Fig.5.7.6**. Fuel Offload variations with Offload/WFB_{tot} are compared with the other tankers in Section 5.9.

5.8. A400M MRTT

As discussed in Ref.2, the A400M, **Fig.5.8.1**, has been designed and developed to meet the European Staff Requirements for a future military transport aircraft with tactical and strategic capability. Initial plans included options for conversion to AAR tanker, **Fig.5.8.2**. Trailing drogue units can be fitted to the multi-role attachment point on each wing in a matter of hours. An optional centerline pallet mounted hose and drogue unit may be carried in the rear cargo bay. The fuel capacity can be increased by 26,500 lb using roll-on/off cargo bay tanks. This takes the total fuel capacity to 132,278 lb and MTOW to 300,931 lb (2.25g limit).

The basic performance data used has been taken from Ref.34, MIL-C-5011B reserves. Payload – Range and field performance data are shown in **Fig.5.8.3**. The weights and range data derived are shown in the tables below.

	MTOW	**TOW**	**OEW**	**WFT**	**WP**	**Range**
Transport	300931	300931	168653		28081	4238
Tanker	300931	300932	168653	132278		

Assuming Fuel Reserves (WFR) of 4% of MTOW at point B, we determine X = 12341 nm and for WFR = 7% of MTOW, X = 14077 nm, Ref.2. This “aerodynamic” efficiency is held constant over the applicable flight envelope region of interest. **Fig.5.8.4** shows the iso-PRE lines super-imposed on the payload – range diagram for WFR = 7% of MTOW, 2.25g operation. Manufacturers payload – range points have been added for confirmation. The efficiency parameter and reserve fuel ratios are used to reproduce the Fuel Offload – Deployment Radius characteristics, **Fig.5.8.5**. We have assumed a fuel transfer rate of 5,300 lb fuel per minute (two hose and drogue units) and 200 kt during transfer. The resulting Fuel Offload, Radius, TOS diagram is shown in **Fig.5.8.6**, solid lines for reserves of 7% of MTOW and X = 14077 nm and dashed lines for 4% reserves, X = 12341 nm. Ref.17 quotes 90,000 lb transferable fuel (no range specified). This corresponds to the estimated offload at 400 nm radius, 2.25g operation, reserves of 7% of MTOW and with zero hours on station. Fuel Offload variations with Offload/WFB_{tot} are compared with the other tankers next.

5.9. Tanker Performance Comparisons (Turbo-jet / Turbo-fan / Turbo-prop)

Certain key capabilities define a tanker’s overall effectiveness. These include

- **fuel available** for offload at given radius
  - in general, larger aircraft have more fuel available for transfer
- **fuel consumed** to complete the mission
  - both aerodynamic and engine efficiency are factors
- **Take-Off field length** requirements at mission TOW
  - only smaller tankers with high lift devices can operate from short airfields.
- **speed range** over which a tanker can successfully refuel receiver aircraft
  - wide range is convenient but operating large aircraft at low speed is inefficient
- **fuel transfer rate**
  - limited by type (boom or hose and drogue) and technology level.

Current and future developments can be retro-fitted to existing tankers

In Ref.38, similar tanker capability parameters were assessed with reference to the USAF tanker replacement programme. Comparisons were made between the KC-30, KC-767 and the KC-135R and presented in the form of a “spider” chart. These will be discussed later.

Estimated variation of Offload available with operating radius is shown in **Fig.5.9.1** for all the tankers considered. The effect of transfer rate on offload available is small but noticeable (A310MRTT 8000 and 2000 lb/min). The higher transfer rate implies that the tanker burns less fuel during the operation resulting in more fuel being available for transfer. The effects of fuel reserves assumed in the estimation of Range Factor (X) is again small but noticeable (KC-130J and A400M 4% and 7% of MTOW). The gradients (offload per radius of operation) are reasonably consistent with the exception of the KC-135R and the KC-130J. These two tankers have a lower “decay rate” (offload deterioration with radius of operation). In the case of the KC-135R this may be attributable to the recent re-engine programme, ensuring that the tanker is significantly more efficient. The KC-130J is a turbo-prop aircraft operating at relatively low speed. The A400M is also turbo-prop but capable of operating speeds approaching those of the turbo-jet aircraft. However, for the purposes of the current exercise, the refuel operating speeds used are 300 kt for the turbo-jet tankers and 200 kt for the turbo-prop tankers.

We note the similarity in capability at 1000 nm radius of operation for the KC-135A, KC-135R, KC-767 and A310MRTT. MTOW for these aircraft ranges from 320,000 to 395,000 lb. Although larger at MTOW 513,000 lb, the A330MRTT does not have a proportionally higher Offload. The much larger KC-10A (MTOW 590,000 lb) has significantly larger offload capability. Estimated data for the KC-767 compares well with manufacturers estimates from **Fig.5.6.1**. The estimated capability of the KC-135R does not compare well with the data supplied by the manufacturers in **Fig.5.6.1**. However, claims in Ref.17 that the KC-135R has 50% better Offload capability at 2000 nm radius of operation than the KC-135A are confirmed by the theory.

The variation of Offload capability with ratio of fuel given to fuel consumed (Offload v Offload / WFB) are plotted for all the tankers considered in **Fig.5.9.2**. This immediately suggests that the KC-10A is by far the most efficient tanker available. However, we need to consider specific operational requirements to make valid comparisons.

Only the KC-10A is capable of supplying 100,000 lb offload fuel at a radius of 1700 nm. Three tankers could provide at least 100,000 lb of offload fuel at 2000 nm radius (KC-10A, A330MRTT and KC-135R). To provide exactly 100,000 lb at 2000 nm radius each of the three tankers would Take-Off below MTOW. At MTOW conditions, the offload / fuel consumed ratio for the KC-135R is 1.137 lb/lb. The A330MRTT and the KC-10A are not so efficient at 0.858 and 0.472 lb/lb respectively. Whilst all the tankers are capable of offloading 40,000 lb at 1500 nm radius we can see from **Fig.5.9.2** that the turbo-prop tankers are far more efficient in terms of fuel consumed. At this requirement the A400M is twice as fuel efficient as the best of the turbo-jet tankers and the KC-130J is twice as fuel efficient again. This highlights the need for careful selection of the best tanker for particular operations. These aspects are further clarified when variations of TPRE are studied.

At this stage we have not taken into account specific penalties at off design operation for the tankers, e.g. increased fuel consumption at low altitude and low speed, increased incidence and hence drag to maintain lift at low speed, etc. When sufficient data are available these aspects can be revisited.

TPRE levels

Tanker Payload Range Efficiency (TPRE) variations with Radius of Operation are shown in **Figs.5.9.3-6** for tankers operating at MTOW. For these comparisons, Jet tanker refuelling speed is 300 kt and 200 kt for the turbo-prop tankers. A typical "offload rate" has been selected for each tanker. The jet tankers (KC-135A & R, KC-10A, KC-767, A310MRTT) are assumed to offload through a centreline boom at a rate of 8000 lb/min. The A330MRTT is offloading at 5600 lb/min via two hose and drogue units. The KC-130J transfer rate is 4000 lb/min (two hose & drogue units) and 5300 lb/min for the A400M (two hose & drogue units).

Jet tanker results are shown in **Fig.5.9.3** for zero hours on station and in **Fig.5.9.4** for eight hours on station. The turbo-prop tanker results are shown in **Fig.5.9.5** for zero hours on station and in **Fig.5.9.6** for eight hours on station. KC-135R and A310MRTT results have also been included with the turbo-prop data for comparison. Peak efficiency for the jet tankers, zero hours on station, occurs at about 1000 nm radius of operation. At this condition, TPRE varies from 2075 nm for the A310MRTT to 3425 nm for the KC-135R. We note from **Fig.5.9.1** that the KC-135R also has a better offload capability. For the majority of tankers there is a 15% to 20% drop in TPRE at 2000 nm radius of operation compared to the peak values at 1000 nm radius. The KC-135A has peak TPRE at about 600 nm radius which falls by 35% at 2000 nm radius. This clearly indicates that the more modern and re-engined tankers have more consistent efficiency levels at varying radius of operation. Assuming the tankers are required to loiter for eight hours on station before refuelling operations commence, efficiency levels fall markedly. There is also a shift in radius of operation for peak TPRE (1000 nm for the KC-135A and 1500 nm for the KC-135R). The KC-10A efficiency levels are comparable to the KC-135R although it has 67% greater offload capability at 1500 nm.

TPRE variation with Radius of Operation, for varying quantities of Offload, is shown in **Fig.5.9.7** for the A330MRTT. TPRE variation with Radius at MTOW (**Fig.5.9.3**) is also shown. For very small Offload quantities (20,000 lb), TPRE remains almost constant at approximately 400 nm to 450 nm. As Offload increases, TPRE varies significantly with Radius, increasing from low values at low Radius to the maximum achievable at MTOW. Similar analysis for the KC-10A is shown in **Fig.5.9.8**. In this case (a much larger tanker), small Offloads (20,000 lb) produce very low TPRE values, 385 nm at Radius of 2000 nm compared to 450 nm for the A330MRTT.

The performance of these two aircraft is again compared in **Fig.5.9.9**, showing the variation of TPRE with Offload for constant Radius of Operation. Here we can see that the A330MRTT is limited to a maximum offload of 100,000 lb at 2000 nm Radius, resulting in TPRE of 2000 nm. For the same operation (100,000 lb at 2000 nm) the KC-10A is 15% less efficient. Similarly, at 1000 nm Radius the A330MRTT is limited to 140,000 lb offload, TPRE = 2435 nm. The KC-10A is 12% less efficient. However, the A330MRTT is not capable of giving the large offloads achieved by the KC-10A at 1000 nm and 2000 nm Radius, 180,000 lb and 240,000 lb respectively.

To further the efficiency analysis, TPRE carpet plots for each tanker need to be derived for varying quantities of offload at various radii of operation.

Tanker and Field length Considerations

Take-off field length requirements for similar operations are important comparisons between the various tanker aircraft. Consistent data is difficult to obtain. Some manufacturers give Take-Off field length to 50ft, others to 35ft. In some cases Take-Off run (brakes off to wheels off) is quoted, in others, Balanced Field Length is given. **Fig.5.9.10** shows typical variation of Take-Off field length with TOW. Fairly comprehensive data was available for the

A330MRTT, the A400M and the C-130J. Take-Off field length for the two turbo-prop tankers is for 50 ft obstacle clearance. Two freighter aircraft, B747-400F and B767-300F, have also been included to confirm the trends. Data from **Fig.5.2.7** for the A310MRTT have been converted to TOW variation with Take-Off distance and plotted in **Fig.5.9.10**. The trends for these six aircraft are shown as solid lines in **Fig.5.9.10**. They fall into a reasonably consistent pattern. Specific points (Offload – Take-Off distance) are known for the KC-135A and the KC-10A. It is not known if the KC-135A take-off performance is augmented in this case. Trends through these points are shown as dashed lines in **Fig.5.9.10** following the patterns established for the other tankers. Take-Off distance variation with Offload at 1000 nm radius of operation (zero time on station) is shown in **Fig.5.9.11** for the tankers analysed.

For the specific mission of delivering 100,000 lb fuel at 1000 nm radius the KC-10A would require a Take-Off distance of 5700 ft. The KC-767 would need 6500 ft and the A330MRTT 6800 ft. The KC-135A and the A310MRTT would need 7600 ft and 7800 ft respectively.

This type of analysis needs to be extended to include tankers operating at less than MTOW to deliver various specific offloads.

Overall capability comparisons – "Spider Chart" A330 MRTT Reference Tanker

Max Offload capability
Take-Off distance
Efficiency
Operating costs (age, spares, maintenance, etc) – *to be completed*.

Design Space and Operational Changes to Improve Fuel Efficiency of Tankers

Dedicated Tanker design
Blended Wing Body, Joined Wing or Conventional layout:-
Wing tanks used to maximum
Reduced diameter / length fuselage (100% fuel density)

Optimised conversion of existing Transports
Wing tanks used to maximum
Fuselage fuel capacity increased
– requires higher MTOW hence structural changes (undercarriage)

Careful selection of most appropriate tanker for task (capacity, altitude, speed)

Careful programming of Training missions

6. RECONNAISSANCE / SURVEILLANCE AIRCRAFT

6.1. General

Airborne intelligence gathering evolved in response to the threat posed by large, national military organisations. To some extent that threat has been superseded by more diverse tactical operations. Consequently, airborne intelligence gathering systems (aircraft, data acquisition, storage, transmission, etc.) have not only undergone widespread upgrades over the past 50 years but are currently undergoing significant developments (e.g. the introduction of UAV and UCAV).

The roles of the reconnaissance, surveillance, communications and command and control aircraft are diverse. In many cases their capabilities are multi-role. Their fundamental requirement is endurance, whether long ranges or extended duration on station. For simplicity, we shall, in general, refer to these aircraft as surveillance aircraft. Some acronyms currently in use:

JSTARS - Joint Surveillance Target Attack Radar System
ISTAR - Intelligence Surveillance Target Acquisition Reconnaissance
AEW - Airborne Early Warning
AWACS - Airborne Warning and Control System
ELINT - Electronic intelligence
SIGINT - Signals intelligence
COMINT - Communications intelligence

The majority of current, in service, surveillance aircraft are derived from civil or military transport aircraft. The development and implementation of airborne surveillance equipment has been constrained by the capacity of the airframe to which it is fitted. Consequently it may be highly integrated into the airframe. The USAF, its allies and NATO, has a large fleet of B707 derivatives performing the surveillance role. The equipment carried in these aircraft has been developed over five decades. MTOW for these aircraft is in the region of 350,000 lb. Recently, Boeing offered the B767 (MTOW near 380,000 lb) airframe as a replacement for the B707 derivatives.

The next generation of surveillance aircraft are likely to be unmanned and designed specifically to task, e.g. HALE, MALE, etc. They are likely to operate in a variety of ways. Long endurance surveillance, monitoring build-up or movement of "targets" or quick response reconnaissance to pin-point and assess the magnitude of priority threats. The two extremes will not "cross-operate". For example HALE craft cannot be deployed at low altitude, high speed, to pin-point troop and armoured vehicle movements minute by minute.

The following table lists the surveillance aircraft assessed in this section, with a primary source reference for each. Details of MTOW, OEW, WFT, Cruise speed and Endurance obtained from the primary reference are shown.

Aircraft	Ref	MTOW (lb)	OEW (lb)	WFT (lb)	Vcruise (kt)	Endurance (hr) – Radius
B737 AEW	24	171000	102750		410	9.3
E-767	27	377000	188705		400	13.0 - 300 nm
E-3	23	347000		155000	313	16
E-3B/C	23					8
E-4B	23	(800000)				12
E-6B	23	342000			522	12.6
E-8C	23	336000	171000	155000	390-510	9
RC-135	23	297000	173000	130000	435	9
RC-135	31	322500	98466			(7)
RC-135S/U	23				350	13.2
RC-135V/W	23				435	10.6
RC-135V/W	27	336000	171000	155000	(435)	11.0
EC-130E	23					1500nm
EC-130J	23					2300nm
U-2S	23	40000	16000	20000	356	20

RQ-4A	23				339	35-39
RQ-4A	24	25600	9200	14500	(333)	42
RQ-4B	24	32250	-	-	(333)	33
MQ-9	46	10500	4900	4000	150-170	14-34

Data from the above table are summarised in **Fig.6.1.1** in terms of Endurance (hrs) against TOW of the aircraft. The figure serves as a useful reminder of the diversity amongst surveillance aircraft. It also highlights the scatter in the published data, e.g. endurance quoted for the E-3 aircraft ranges from 8 to 16 hr. Similarly there are ranges of TOW and Endurance quoted for the C-135 series of aircraft. The turbo-prop powered MQ-9 (TOW 10,500 lb) lies close to the endurance scale (vertical) in **Fig.6.1.1** and ranges from 14 to 34 hrs without significant increases in TOW.

Noting that the surveillance payload is highly integrated into the surveillance aircraft OEW we have derived an effective Pt B (maximum fuel) Range. The aircraft component weight breakdown ratios with respect to MTOW are shown in **Fig.6.1.2** together with the civil freighter trends. The surveillance aircraft data lie on or close to these trends. The trends can be extended to very long ranges to encompass the unmanned RQ-4 (Global Hawk) aircraft. There is insufficient, reliable data to analyse the turbo-prop powered MQ-9 in this way.

The surveillance aircraft have been analysed and compared using two efficiency metrics. The first is based simply on Endurance and Fuel consumed. The second requires an accurate assessment of “useful” payload. As noted earlier, the surveillance equipment (antennae, computers, power supply, operators, etc) is frequently included in the quoted OEW for this classification of aircraft. In the case of the un-manned Predator for example, additional disposable payload is often quoted. Further work is required to establish more precise comparisons using both metrics. This will require a more unified database for surveillance aircraft that will include:

Take-Off weight
Fuel Capacity
Basic OEW (Airframe, Powerplant, Flight systems)
Surveillance Payload (Antennae, computers, power supplies, operators)
Disposable Payload
Endurance (hr) at various Radii of Operation
Deployment and Loiter Speeds

Data available at present may include some or all of the above, in varying degrees of accuracy. We have made a preliminary assessment of each aircraft based on available data.

The variation of wingspan (b ft) with MTOW is shown in **Fig.6.1.3** for the surveillance aircraft, together with the civil and military transport trends. Naturally, the B707 derivatives (E-3, E-6, E-8) lie close to the civil trends. The early military derivative, RC-135 also lies on the civil transport trends. Both the E-4B and the 737 AEW&C lie close to their civil transport originals. Both the U-2 (manned) and RQ-4 (un-manned) are small aircraft with high AR wings. They form a unique group in the span – TOW envelope. Similarly, the turbo-prop powered MQ-9 falls within this category.

The payload, weights and range information assimilated for each of the surveillance aircraft, together with analysis of equivalent civil aircraft, where applicable, has resulted in a wide variation of Range Parameter (X). Values used for individual aircraft are given in each of the following sections. The values are compared and discussed in Section 6.11.

6.2 Boeing RC-135S Cobra Ball, RC-135U Combat Sent, RC-135V/W Rivet Joint

The Boeing C-135 and RC-135 families of military aircraft are derivatives of the Boeing 707 civil airliner, **Fig.4.1.1**. In some cases the surveillance aircraft are modified variants of the KC-135 Tanker / Transport aircraft, whilst others are conversions from civil airframes or "new build". Naturally, complete and accurate data for the military aircraft are difficult to obtain. However we are able to couple published data with knowledge of the civilian airframe performance to build up a reasonable understanding of efficiency.

Currently the RC-135 performs three surveillance and reconnaissance roles (Refs.17,48). Three RC-135S Cobra Ball aircraft are in service with the USAF, to detect and monitor missile testing. Two electronic intelligence (ELINT) gathering RC-135U Combat Sent aircraft are in service. Sixteen RC-135V/W Rivet Joint aircraft, eight of each type, perform the signals intelligence (SIGINT) role, specialising in communications intelligence (COMINT).

Nominally, RC-135 aircraft types have MTOW of 300,000 to 320,000 lb, are fitted with PW TF33-P5/9 engines and have AAR capability, Refs.17,48. The aircraft are currently being re-engined with CFM56 (F108) turbofans to increase unrefuelled range and endurance. Additional data for the RC-135V have been obtained from Ref.22 for comparison with the tanker variants as follows:

	TOW	OEW	WP	Range	
RC-135V	317466	105050		4645	based on Op radius of 2323 nm
KC-135A	309600	106307			PW J57-P-59W turbojet engines
KC-135R	322500	119212			F108-CF-100 turbofan engines

Fig.6.2.1 shows the payload – range diagram for the B707-320B civil airliner. Also plotted on this diagram are MTOW and equivalent operational range coordinates for the RC-135V and OC-135 surveillance aircraft. Data for other B707 derived surveillance aircraft such as the E-3 and E-6 are also included and will be discussed relevant sections. This figure confirms the general validity of the derived data although it is noted that quoted OEW for the various aircraft differ considerably.

An estimated total weight breakdown for the B707-320B, KC-135A, E-3A, E-6A and KC-135V is given in **Fig.6.2.2**. We note the increased fuel capacity of the KC-135A tanker compared to that of the B707-320B. This is afforded by the additional fuel tanks fitted for the tanker role. An OEW+WP (equipped) value for the RC-135V/W has been derived assuming a known TOW and fuel capacity of the B707-320B.

	TOW	OEW	WP	Endurance
RC-135V/W	336000	181000	includes effective payload	

Based on B707-320 performance, an estimated X value of 9500 nm has been used for analysis of the RC-135V/W.

6.3 Boeing E-6A Mercury, Tacamo (Boeing 707-320B)

The E-6A Mercury, **Fig.4.1.2**, operates as a submarine communication platform and is based on the Boeing 707-320. It replaces C-130 Hercules aircraft in this role. Its primary requirement is long endurance on station, trailing a very long aerial. To achieve this it cruises at low speed (454 kt) in tight, near circular orbits. It is fitted with CFM-56 engines totalling 96000 lb thrust.

A typical mission is 10.5 hrs on station (454 kt), 1000 nm radius from base. Total flight distance is therefore of the order of 6800 nm (a significant portion at loiter). Total unrefuelled range is quoted as 6340 nm, assuming normal cruise speed. This gives some indication of the fuel savings that can be achieved by reducing speed.

Data obtained from various sources (Refs.17,48) are shown below and compared with typical B707-320 data.

	TOW	OEW		WP	WFT	Range	
B707-320B	333600	148800		25840	158960	5150	545 kt
E-6A	341281	172431	+	14172	154678	6340	

Fig.6.2.1 shows the payload – range diagram for the B707-320B civil airliner. Also plotted on this diagram are MTOW and equivalent operational range coordinates for the E-6A. This figure confirms the general validity of the derived data. We note the OEW for the E-6A is some 24,000 lb higher than the B707-320B. This correlates well in terms of payload-range in **Fig.6.2.1** and represents equivalent weight of surveillance equipment carried. The more efficient CFM engines (total thrust 96000 lb) fitted to the E-6A greatly improve the range capability over the JT3P powered B707-320B (total thrust 76000 lb). The effective X value used is 10,000 nm. This reflects the improved engine performance of the E-6 coupled with the degradation in performance due to the trailing antennae.

From the above data, a total weight breakdown diagram for the E-6A is compared with the B707-320 in **Fig.6.2.2**.

6.4 Boeing E-3A to F AWACS, AEW

The Boeing E-3, **Fig.4.1.1**, exists in several modes E-3A to E-3F and serves with several NATO airforces. It is an airborne warning and control system (AWACS), also referred to as AEW (airborne early warning). It uses multi-mode radar to detect airborne, maritime or land targets. It is fitted with either PW TF33-P-100A (USAF and NATO) or GE CF6-50E (UK and France) turbo-fan engines. Data obtained from various sources (Refs.17, 48) for the E-3D are shown below.

The E-3 is based on the Boeing 707 and both carry all their fuel in wing tanks. There are no additional fuselage, tip or ferry tanks. We can therefore use the performance of the B707-320B at Pt B (max fuel capacity) to enhance the limited data available for the E-3. We note that the performance data for the B707-320 applies to the much older JT3-P engines. Converting the basic B707 type airframe for use as E-3 requires strengthening of the floor and additional bulkheads to accommodate the “Rotodome”. Radar equipment, scanners, aerials, computers and other electronic hardware are highly integrated into the E-3 airframe. Various “OEW” values are quoted for the E-3. An OEW of 188000 includes airframe, all electronic warfare equipment, operators and, naturally, floor strengthening and additional bulkheads. We can estimate an overall value for WPB by assuming that the E-3 basic OEW is 0.95 x B707-320B OEW, i.e. seats, galleys, entertainment items removed. This will be useful in establishing comparisons with a possible airframe replacement, e.g. E-767.

	TOW	OEW	WPB	WFTB	Range	
B707-320B	333600	148800	25840	158960	5150	
E-3A	325000	171996			11 hrs	Ref.22
E-3D	325000	170256			11 hrs	Ref.22
E-3A/B/C/D	354504	188000				Ref.17
E-3A	332500			155448	5000+	
E-3D	352000	188000	(7545	164000)		

We note from the above data, the diversity of the available information. Ref.17 does not distinguish between the E-3A, B, C and D in terms of MTOW, OEW or engines fitted (PW TF-33-P-100A). Similarly, Ref.22, acknowledges that the E-3D AEW.Mk 1 is fitted with much more powerful and fuel efficient engines (CFM56-2A2) than the E-3A AWACS Sentry (PW TF-33-P-100/100A) but quotes identical endurance.

The payload – range diagram for the B707-320B is shown in **Fig.6.2.1**. MTOW for the B707-320B is 333600 lb. If the lines of constant TOW are projected from 330000 to 340000, 350000 and 360000, the possible "single-point" operation of the E-3D is encompassed at a MTOW of approximately 352000 lb. This might imply that the "Rotodome" does not impair performance or significantly increase drag. However, the "Rotodome" reduces the E-767 range by some 15% when compared with civil B-767 with the same engines. If the B707-320B were fitted with equivalent modern engines, a similar short-fall in range due to drag of the "Rotodome" might be apparent. This conclusion is confirmed by the fact that the E-3 has 20% less range than the E-6A, both fitted with comparable modern engines but the E-6A is not impaired by the presence of a "Rotodome" only a trailing antennae. Consequently, on balance, we have retained the X value derived for the civil aircraft. This results in predicted performance agreeing well with quoted data.

6.5 Boeing E-767 AWACS, AEW

Boeing offered the B767-200ER, **Fig.4.1.5**, airframe as a possible E-3 (B707) replacement. Two "demonstrators" were built and evaluated. The option was not taken up by USAF or NATO. Japan purchased and operate four E-767. Both the B767-200ER and the E-767 use CF6-80C2 engines.

We use the performance of the B767-200ER at Pt B (max fuel capacity) to enhance the limited data available for the E-767. As for the B707 conversions to E-3, the E-767 has strengthened floors and additional bulkheads to accommodate the "Rotodome". It is assumed that the surveillance equipment fitted to the E-767 is similar to that in the E-3 aircraft. We take 0.95 x B767-200ER OEW and add a suitable weight to represent the surveillance equipment. This results in an "OEW" of approximately 222000 lb.

	TOW	**OEW**	**WPB**	**WFTB**	**Range**
B767-200ER	386000	182900	41300	161800	6779
E-767	377000	222000		155000	5600

The payload – range diagram for the B767-200ER is shown in **Fig.6.5.1**. Assuming MTOW of 377000 lb for the E-767 we estimate a comparable range of 6600 nm. However, a quoted range of 5600 nm for the E-767 suggests a loss of 1000 nm range capability, due to the drag of the "Rotodome", although using similar engines. The effective X value used is 10,000 nm. This reflects the degradation in performance due to the rotodome.

6.6. Boeing E-4

The Boeing E-4, **Fig.4.1.4**, is a highly sophisticated command and control centre based on the B747-400. It would be used by the National Command Authority in times of crisis. The Range Factor (X) derived for the B747-400 is approximately 14500 nm. The E-4 has several large fairings on the fuselage which house ECM and Communication equipment. We therefore reduce X to 14000 nm for evaluation purposes. It is understood that no additional fuel tanks are fitted to the E-4. The assimilated data gives:

	MTOW	**TOW**	**OEW**	**WPB**	**WFT**	**Range**
B747-400	850000	843900	394000	88200	361700	6800
B747-400		800000	394000	44300	361700	7250
E-4		800000	438300		361700	

An endurance of 12 hrs is quoted in the literature. Using the above data, theory predicts an endurance of 13 hrs.

6.7. Lockheed U-2S

The Lockheed U-2S, **Fig.4.1.6**, and its predecessors have been in service for more that fifty years. It is a single seat, single engine, tactical reconnaissance aircraft of unique design (high AR, unswept wing) with an endurance of twenty hours. Assimilated data gives:

	MTOW	TOW	OEW	WFT	Range
U-2S	40000	40000	16000	20000	7120 @ 356 kt

The U-2S carries 3000 lb payload. We note, with caution, that all weights are quoted to the nearest 1000 lb. The estimated Range Parameter (X) value, of just over 12,000 nm, has been reduced to 10,000 nm for subsequent analysis and comparisons.

6.8. Unmanned Reconnaissance Vehicles RQ-4A/B/N (Global Hawk), MQ-9 (Reaper)

Global Hawk RQ-4A & B/N

The Northrop Grumman Global Hawk (RQ-4B/N), **Fig.4.1.7**, is a high altitude, long endurance UAV. It is currently in service with, or soon to be procured by, the USAF, US Navy, RAF and several other nations. It is a larger derivative of the RQ-4A. Both are powered by a single Rolls-Royce AE3007H turbofan engine. Very limited data are available (Ref.40):

	MTOW	OEW	WFT	WP	Endurance
RQ-4A	25600	9200	14500	1900	35/39/42 hr
RQ-4B/N	32250	13250	16000	3000	33

It is not clear from the available sources whether the payload is included in the fuel or as part of the OEW. For the present purposes we have assumed fuel carried is the difference between MTOW and OEW. Further clarification is required. The Range Factor (X) derived is approximately 16500 nm for both aircraft. At first, this value appears extremely high but we note that this is a sophisticated, modern, unmanned aircraft, with very high AR wings. The derived endurance (zero radius from base) agrees well with the given data. Data from another source, implying that the 3000 lb payload is not part of the quoted OEW, renders a lower X value (13,500 nm). However, using this value in the analysis results in endurances that are not supported by the available data.

Reaper MQ-1 & 9

The MQ-9 (Reaper, also referred to as the Predator-B) is much larger than its predecessor, the MQ-1 Predator. Initially developed as a surveillance aircraft, it is now capable of long endurance and significant stores carriage. This allows extensive monitoring of targets to ensure correct designation before accurate weapon delivery.

Range, Endurance, TOW, OEW and WP data for the Reaper varies significantly between sources. Basic, current information from Ref.17 includes TOW: 10,500 lb, span: 66 ft, max altitude: 50,000 ft, V: 209 kt, Endurance: 30+ hr and powerplant: Honeywell TPE331-10. Other sources claim endurance of 14 hrs when fully loaded, maximum speed: 260 kt and cruise speed: 150-170 kt. Without external stores at TOW: 10,000, WP:3000, Fuel: 3000, the Reaper has an endurance of 32 hrs at 50,000 ft. If the wings are extended to 86 ft span, internal fuel content is increased to give an endurance of 34 hrs. With 1000 lb drop tanks and WP: 1000 lb, the endurance increases to 42 hrs. Most sources agree on store carriage arrangements of fourteen Hellfire missiles or four Hellfire missiles and two 500 lb Laser Guided Bombs (LGB) on six wing hardpoints. We note that the Hellfire missiles weigh approximately 105 lb each and the 500 lb LGBs weigh approximately 610 lb.

Using our conventional anlysis method, without allowance for fuel consumed to start of cruise condition, we estimate range parameter (X) of 5225 nm. At V: 150 kt, sfc: 0.55

(TPE331-10) this equates to L/D: 19. The long endurance figures quoted imply a loiter speed of approximately 50 kt. These need to be verified before further inferences can be drawn.

6.9. Boeing / Northrop Grumman E-8C (JSTARS)

The initial variant (two prototypes) of the Boeing / Northrop Grumman E-8C, **Fig.4.1.1**, was first used in 1991. It was converted from civilian Boeing 707-320 airframes. Brief data are available as follows:

	TOW	OEW	WPB	WFTB	Range
B707-320B	333600	148800	25840	158960	5150
E-8C	336000	181000		155000	9-11 hrs Ref.22

The current engines (JT8D-219, 21,700 lb thrust) are 17% more fuel efficient than the original TF33-PW-102A (18,000 lb thrust). Increasing X from 9493 nm (B707-320) to 10,000 nm gave good correlation with endurances quoted. It is anticipated that the more modern engines would have increased X by a greater margin. The deficit is possibly due to the mode of operation and the large antennae housing under the forward fuselage.

6.10. Boeing 737-AEW "Wedgetail"

The Boeing 737 has been developed into several civil variants over many decades. MTOW ranges from 138,500 lb for the –300 to 187,700 lb for the –900ERW. The -200 airframe was developed to provide Airborne Early Warning capability as the 737-AEW, **Fig.4.1.3**, with significantly increased MTOW. Available data are:

	TOW	OEW	WPB	WFTB	Range
B737-200	115500	60170			
737 AEW	171000	115000		56000	9.3 hrs Ref.22

The current engines (CFM56-7B27A) provide 54,600 lb thrust. This is greater than the thrust available on the civil variant. The effective X parameter, that allows a balanced agreement with quoted performance is 12,513 nm (as for the civil 737-700).

6.11. Comparisons

For meaningful, comparisons to be made, reasonably accurate assessments of Range Parameter X are required. X may derived from a knowledge of fuel burn and range (endurance and speed) or from speed, L/D and specific fuel consumption. Prior knowledge of X values estimated for the civil versions (X Civ Eq) from which many of the surveillance aircraft have been derived has been useful. Where insufficient data are available to establish X for the surveillance aircraft (X Est), X Civ Eq is used to make initial estimates. The input parameters (weights, range, endurance, X, etc) are then adjusted, using prior knowledge of trends and the effects of technology improvements, to ensure that performance results derived for each surveillance aircraft match verified data given.

The following table lists the surveillance aircraft and X Est values used for the current analysis. Also shown are the civil equivalent aircraft, where applicable, and X Civ Eq. Possible reasons for the resultant modified X values are given.

Aircraft	Civil Equivalent	X Civ Eq	X Est	Comments
737-AEW	B737-700	12513	12513	Relatively small, low drag antennae
E-3B/C	B707-320	9493	9493	Large Rotodome, Re-engined
E-4B	B747-400	14585	14000	
E-6B	B707-320	9493	10000	Trailing aerial, Re-engined

E-8C	B707-320	9493	10000	Large antennae housing, Re-engined
RC-135V/W	B707-320	9493	9500	Large antennae housing, Re-engined
RQ-4A			16500	High X derived from available data
RQ-4B/N			16500	High X derived from available data
U-2S		12177	10000	Rounded weights data –optimistic?
E767	B767-200ER	15421	10000	Large Rotodome added
MQ-9			5225	Low X derived, turbo-prop

Surveillance Aircraft Metrics

For civil and military transport aircraft, efficiency in terms of payload, range flown and fuel consumed is readily quantifiable (PRE = WP * R / WFB). For the tankers we define a similar parameter, TPRE, a function of Offload available at Radius of operation and tanker fuel consumed (TPRE = Offload * Radius / WFB).

Surveillance and reconnaissance aircraft pose a more difficult problem. The payload (cameras, sensors, scanners, operators, etc.) is highly integrated into the aircraft structure and, in general, cannot be accurately quantified. Surveillance aircraft efficiency is most readily quantified in terms of Loiter time (t_L) at radius of operation (R_{SO}) and fuel consumed:

SRE = Loiter (hr) * Radius (nm) / WFB (lb) = $t_L * R_{SO}$ / WFB [hr*nm/lb]

An alternative metric is considered, Ref.49, which takes into account the useful payload (surveillance equipment and operators) to fuel burn ratio, radius of operation and effective endurance parameter. We can then define :

SPRE = Payload (lb) / WFB (lb) * (2*Radius (nm) + Loiter (hr) * speed of sound (nm/hr))

= WP/WFB * (2*R_{SO} + t_L*a) [nm]

Whilst an attempt has been made to balance the published performance data with the theoretical results it is evident that more detailed consistent data are required. For example, aircraft weight breakdown (MTOW, OEW, WP, WFT), Endurance at various Radii of Operation and respective speeds (loiter and deployment) or fuel consumption rate variation with speed.

Fig. 6.11.1 shows the variation of time on station (endurance, hrs) against operational radius. This type of information has only been quoted for the E-767 (13 hrs at 300 nm radius and 9.25 hrs at 1000 nm radius). Overall endurance has been quoted for the other aircraft assessed. These points are shown as large symbols on the axis at radius = 0 nm. The theory correlates well with the given data.

SPRE levels

The variation of SPRE with Radius of Operations is shown in **Fig. 6.11.2** for the conventional, manned aircraft. SPRE ranges from zero to approximately 0.1 hr.nm/lb. At a radius of operation of 1000 nm, the 737 AEW is twice as efficient as the RC-135V/W. However, these two aircraft may not be carrying the same types of surveillance equipment or the same number of operators. The E-767 AWACS and the 737 AEW carry out similar roles although the much larger E-767 carries more equipment and more personnel.

The variation of SPRE with Radius of Operations for the U-2S and the unmanned RQ-4 is shown in **Fig. 6.11.3**. SPRE ranges from zero to approximately 6.0 hr.nm/lb. Note the changes in vertical and horizontal scales between **Figs.6.11.2** and **3**. The RQ-4B/N is a development of the RQ-4A, 27% heavier, 7% longer with 13% greater span. Although the

RQ-4B/N has a lower SPRE at 3500 nm radius of operation, it carries 58% more payload. If we include WP into efficiency parameter (WP * E * Radius / WFB) both variants have very similar efficiencies.

At a radius of operation of 1000 nm, the 737 AEW is twice as efficient as the RC-135V/W.

Field length

Take-off field length requirements for similar operations are important comparisons between the various tanker aircraft. Consistent data is difficult to obtain. Some manufacturers give Take-Off field length to 50ft, others to 35ft. In some cases Take-Off run (brakes off to wheels off) is quoted, in others, Balanced Field Length is given. **Fig.5.2.7** shows typical variation of Take-Off field length with TOW.

We can begin to make some comparisons for specific missions.

Operating costs (age, spares, maintenance, etc)

Overall capability comparisons – "Spider Chart" RC-135V/W Reference Aircraft??~~

RC-135V/W is now reference aircraft# (To Be Done)

Reaper

It is difficult to make direct performance efficiency comparisons between the Reaper and other aircraft since the Reaper now performs a unique role combining surveillance, target designation and weapon delivery. Before the advent of UAVs and UCAVs, surveillance was carried out by aircraft such as the E-3 and the U-2, supported by "in theatre, on the ground" intelligence gathering. Target designation may be carried out by current, manned weapon delivery platforms or by accompanying aircraft dedicated to that role or by personnel operating on the ground, often behind enemy lines. Weapon delivery can vary from relatively inexpensive high level, free fall, "carpet bombing", via operator intensive guided weapon delivery to very expensive, stand-off cruise missile deployment. UCAVs, such as the Predator, combine all these functions whilst the operator functions in relative safety, thousands of miles from the war zone.

7. BOMBERS

7.1. General

In Ref.17, twelve types of aircraft are listed under the Bomber classification. By country of origin and designation these are: B-1B, B-2A, B-52H, F111, Mirage 2000N, Su-22M, Su-24, Su-32, Su-34, Tu-22M, Tu-95 and Tu-160. Of these, the Tu-95 is a subsonic turbo-prop aircraft and the B-52H and B-2A are subsonic turbo-fan aircraft. Each of the remainder has supersonic capability, although not currently used in all cases. The following table broadly classifies the bombers into variable and fixed wing geometry and MTOW. The similarities between Western and Soviet counterparts are noted. We also note that the fixed-wing Tu-22 (Blinder) is significantly different from the Tu-22M (Backfire) and no longer in service.

Aircraft	Wing	Wing Location	Intake	MTOW
Tu-160	Variable	Low	Podded U-Wing	606260
B-1B	Variable	Low	Podded U-Wing	477000
Tu-22M3	Variable	Low	Wing Root U/S	273370
F-111C-G	Variable	High	Wing Root L/S	119250

Su-24MK	Variable	High	Wing Root L/S	96463
B-52H	High-AR	High	Iso Wing	488000
Tu-95M5	High-AR	Mid	(Iso Wing)	407800
B-2A	Flying Wing	-	Upper Surface	336500
Su-32	Low-AR	Mid	Wing Root L/S	84305
Su-34	Low-AR	Mid	Wing Root L/S	97800
Mirage 2000N	Delta	Low	Wing Root U/S	38000
Su-22M3/M4	Variable			43299/42836

Information for the bombers has been obtained from a wide variety of sources. The data are often contradictory. Typical information will include MTOW, OEW, Typical TOW, Typical Payload and a quoted Range or Radius of operation. The bombers may undertake various mission types, e.g. Hi-Hi (High altitude for entire mission), Hi-Lo-Hi (High altitude out and back with Low altitude penetration run), Lo-Lo (Low altitude for entire mission), etc. For each mission type, two scenarios may occur, a "design" operation in which the bomber releases the payload at the mid-range point (typically radius of operation) and returns to base, or the bomber completes its mission without releasing the payload. In general, the derived Payload-Range diagrams, for each aircraft, depict the "Payload retained" scenario. Further clarification is required to precisely define the modes of operation.

We have attempted to establish a range efficiency parameter (X), for each bomber, operating under "conventional" conditions (cruise altitude, cruise speed, Pt.B – maximum fuel with corresponding payload). We have derived an effective Pt B (maximum fuel) Range assuming that the payload is not released. Where the payload is not released the bomber is acting as a transport aircraft and Payload Range Efficiency can be defined conbventionally,

PRE = WP x Range / Total Fuel consumed.

An efficiency parameter, comparable to PRE, is defined for bombers where the payload is released on target. The bomber returns to base with only fuel reserves onboard. Bomber Payload Range Efficiency (BPRE) is given by:

BPRE = Weapon load x Range to Target / Total Fuel consumed by bomber

A similar metric is defined for the tankers in Section## (To be done).

Three bombers are considered in detail and these differ markedly in design and capability. The B-1B is a variable geometry bomber with supersonic capability. The B-2A is a very stealthy, subsonic flying wing. The B-52 is a conventional, high wing subsonic bomber.

The aircraft component weight breakdown ratios with respect to MTOW are shown in **Fig.7.1.1**, Pt B operation, together with the corresponding civil freighter trends. The bomber data follow similar trends. The variation of Thrust to Weight ratio (T/W) with Point B range is shown in **Fig.7.1.2**. The variation of T/W with maximum payload range was shown for the tankers in **Fig.5.1.3**. We note in **Fig.7.1.2** that the B-52 (conventional high wing, tail, fuselage layout) lies within the civil transport trends. The B-2A lies on the military transport 2.50g trend and the B-1B lies on the military transport 2.25g trend close to the civil transports. The values quoted are for Sea Level static thrust at MTOW. Generally, the bombers will take-off at less than MTOW, resulting in shorter Take-Off distances due to higher effective T/W levels. Very little reliable Take-Off distance data were available for the bomber aircraft. Effective comparisons cannot, therefore, be made at this stage. However, for the three bombers considered, under normal operations from suitable airfields well away from the target area, available runway length is not a limiting factor.

The variation of wing span (b ft) with MTOW is shown in **Fig.7.1.3** for the bombers, together with the civil and military transport trends. The B-52 and the B-2A lie close to the transport aircraft trends. In their non-swept state, the variable geometry bombers (B-1B, TU-22MS) lie below the transport trends. With their wings swept, their span effectively halves. In its non-swept state, the TU-160 bomber span lies within the transport trends. When swept at 65^o its span reduces by 40%.

In the following subsections we analyse each aircraft type. Where appropriate a brief analysis is given for a Soviet counterpart.

7.2. B-1B & TU-160

The Boeing (Rockwell) B-1B is a derivative of the Rockwell B-1A. Only four prototype B-1As were built and flown. Currently 67 B-1Bs are in service with the USAF. The Tupolev TU-160 is a very similar but larger aircraft and has been briefly assessed.

Information for the B-1B has been obtained from several sources (Ref.s 17, 28, 37). The aircraft was developed as a low-level strategic bomber. Its variable geometry (swing wing) allows it to operate in a number of modes, high level, low level and various combinations. The range will depend upon the payload carried and the mode of operation. Carrying 24 JDAMS (unspecified), typical modes and ranges are Hi/Hi – 4,400 nm, Hi/Lo/Hi – 4,200 nm and Lo/Lo – 2,200 nm. We can see immediately that its payload-range efficiency doubles when operating at high altitude compared with the low-level mode.

Typical sweep, Mach, Speed and Altitude combinations are given in the table:

Sweep	M	TAS	Altitude	
25.0^o	0.71	440	High	
55.0^o	0.85	510	High	
67.5^o	1.20	700	High	Ref.22 suggests Operational maximum M 0.99
67.5^o	0.85	540	Low	

Data for various mission types and profiles are given in Ref.37. In general, the missions require the use of AAR to complete the specified range. A single case (high altitude, stand-off delivery of 16 ACMs), not requiring AAR, has been used to establish a possible payload-range diagram. A second case, Single Integrated Operational Plan (SIOP) involves a high altitude "out leg" with AAR to achieve the overall required range, a low level penetration, release of 24 SRAMs, low level withdraw and climb to altitude for recovery (Hi-Lo-Hi).

Tanker used	B-1B TOW	OEW	WP	Range	
None	446160	192000	48000	4425	Stand-off, release at 2212 nm
KC-135A	433406	192000	53000	5903	Hi-Lo-Hi, release at 4903 nm
KC-135R	433406	192000	53000	6360	Hi-Lo-Hi, release at 5360 nm
KC-10A	433406	192000	53000	7358	Hi-Lo-Hi, release at 6358 nm

The total weight breakdown variation with distance travelled for the B-1B stand-off mission is shown in **Fig.7.2.1**. We note the nominal fuel burn – distance gradients. The gradient is much steeper (50.4 lb/nm) on the "out leg". After weapon release and with only return fuel and reserves on board the gradient is much lower (30.0 lb/nm). These gradients have been used to assist in the assessment of the Special SIOP missions.

Using the stand-off mission data, an average X value of 8213 nm arises for the B-1B. Total fuel burnt is 177,960 lb and a 48,000 lb payload has been delivered at 2213 nm. Mission efficiency (BPRE) is defined as the product of the payload delivered and the range to target divided by total fuel consumed during the mission. This gives an overall BPRE of 597 nm.

A schematic diagram for the SIOP missions is shown in **Fig.7.2.2**. The overall range (range to target plus recovery range) defines the quantity of fuel required. At TOW of 433,406 lb and payload of 53,040 lb the B-1B has 187,560 lb of fuel onboard. This is insufficient to complete any of the SIOP missions specified. The various tankers have different offload capabilities at different ranges. The AAR fuel uploads required by the B-1B to complete the total ranges are 80,000 lb / 5903 nm, 97,550 lb / 6360 nm (further 457 nm to target) and 132,710 lb / 7358 nm (further 1455 nm to target). These quantities can be offloaded by the KC-135A, the KC-135R and the KC-10A respectively assuming that they operate from bases approximately 2000 nm from the AAR rendezvous point (see **Fig.5.9.1**). Including the fuel consumed by the tanker, overall BPRE / Range-to-target are 603 / 4903, 638 / 5360 and 545 / 6358. The tanker-consumed fuel is based on the offload/WFB ratios determined for each tanker operating at maximum capacity. Although only the KC-10A can deliver 132,710 lb fuel at 2000 nm radius it may not be necessary to operate it at maximum capacity and hence a better efficiency could be achieved at lower TOW.

From this detailed analysis we have been able to establish a Payload – Range diagram, **Fig.7.2.3**, for the B-1B assuming that the payload is not released (transport) mode. This forms the basis for initial comparisons in Section 7.5.

TU-160

The Tupolev TU-160 is similar to, but larger, than the B-1B. Information for the TU-160 has been obtained from several sources (Ref.s 21, 24). It is noted that the difference between Range and Radius of Operation is not clearly defined. The following table summarises typical payload – range combinations claimed.

TOW	OEW	WP	Range
606271	242500	88185	5670
588626	242500	19842	7560

These points have been added to the payload range diagram for the B-1B for comparison, **Fig.7.2.1**. Estimated PRE for the Tu-160 at 6000 nm is of the order of 1600 nm. Trends for the B-1B extended to this range would achieve approximately 1400 nm. Further, confirmed payload - range capabilities for both aircraft are needed for a full comparison to be made.

7.3. B-52 & TU-95M5 (Turbo-prop)

The Boeing B-52 was developed during the early 1950s and 94 B-52H variants are in service with USAF. Wing area and span claims vary from 4000 ft / 185.0 ft to 2923 ft^2 / 176.2 ft for the B-52H. Definition of wing area may vary. Overall AR (based on projected planform) is 8.3. The B-52H is powered by eight engines in four podded pairs, currently PW TF33-P-3 turbofans (17,000 lb thrust each). Various sources make varying capability claims (maximum payload 80,000 lb to 84,327 lb). The B-52 can carry external stores on two wing pylons only, inboard of the inner engine pods. Each pylon accommodates four triple carriers, giving a total of 24 externally carried 1000 lb bombs. It is not clear whether this “additional” capacity is included in the maximum payload claims.

Using the “key points” in the table below and the “family” trends of the B-52, B-707 and B-747 we have established a possible Payload-Range diagram, **Fig.7,3.1**.

TOW	OEW	WP	Range	
488000	185000	80000		A Point
488000	185000	70000	7780	

The payload – range diagram assumes that the payload is not released (transport) mode. This forms the basis for initial comparisons in Section 7.5.

TU-95M5 Bear H (Turbo-prop)

The Tupolev TU-95 is the only strategic bomber equivalent to the B-52 in terms of weight and range. It is a turbo-prop aircraft, powered by four NK-12 (12,000 shp) engines with counter rotating propellers.

TOW	OEW	WP	Range	
414470	198415		3455	Ref.20
407800	192400		8000	Ref.17

Further data on WP is not known at present.

7.4. B-2A

The Northrop Grumman B-2 is powered by four GE F118-GE-100 turbofan engines (19,000 lb thrust each) and 20 are currently in service with USAF. It has wing area of 5140 ft^2 and a span of 172 ft. The AR is approximately 5.8.

Naturally, specific details of the B-2A weights and ranges are difficult to ascertain. It appears to have been designed with very little latitude in terms of fuel load, payload and MTOW, i.e. it has single-point, MTOW, capability as shown in the following table.

TOW	OEW	WP	Range	
373700	153700	40000	4410	Pt A, Pt B and Design coincide

The derived payload – range diagram (payload retained) is shown in **Fig.7.4.1**. This forms the basis for initial comparisons in Section 7.5.

7.5. F-111F

The F-111 was originally conceived as a variable geometry, strike and interdiction, aircraft to replace Republic F-105 (Thunderchief) and McDonnell F4H (Phantom II) for the USAF and US Navy respectively. The F-111A was produced for the USAF by General Dynamics and the F-111B was to be developed for the Navy by Grumman. The F-111A was underpowered and the F-111B was overweight.

Several variants followed, F-111E (improved intakes and avionics), F-111D (19,600 lb thrust engines and new avionics), FB-111A (20,150 lb thrust engines, increased span, nuclear capability), F-111G (trainer, converted FB-111A), F-111K (cancelled), F-111C (export, F-111A avionics, FB-111A span but reduced thrust), RF-11C (F-111C reconnaissance variant) and the F-111F.

The General Dynamics F-111F (Aardvark) is powered by two PW TF30-P-100 turbofan engines (25,100 lb thrust each). Thrust to Weight ratio (T/W) is increased to 0.53 from 0.39 of early variants. At 16.0^o sweep the span is 63.00 ft (area 657.07 ft^2, AR 7.56) and at 72.5^o sweep the span is 31.95 ft (area 525.00 ft^2, AR 1.55).

The F-111F has a weapons bay but this usually houses the AVQ-26 Pave Track pod giving the F-111F autonomous Laser Guided Bomb capability. Stores are carried externally on up to six wing pylons (31,500 lb max, Ref.22). Internal fuel capacity is 33,550 lb and external fuel capacity is 16000 lb (4 x 600 US gal tanks). No verifiable payload – range data are available. Two Maximum range cases are quoted, internal fuel only range is 2540 nm, Ref.21, and with internal and external fuel range is 3100 nm, Ref.27. In neither case is payload defined. Internal and external fuel plus OEW puts the TOW at 97,050 lb which is very close to MTOW. In this case we assume no payload is carried and X equates to 5232 nm. Other combinations of payload, fuel and TOW for the range of 2540 nm result in X varying from 6100 nm to 8100 nm. It is assumed that in these maximum range cases the aircraft operates subsonically and we see from **Fig.4.3.5** that with wings swept at 26^o, L/D is, at best, 15. From

Ref.17 we note that sfc for the TF30-P-100 series is 2.5 to 2.7 at maximum power. Assuming a cruise speed of approximately 500 kt, L/D of 15 and sfc 1.15, X equates to 6500 nm. This very approximate, mean value is used to derive a payload range diagram, for a "clean" configuration, **Fig.7.5.1**. At maximum fuel capacity and MTOW, X falls to approximately 5250 nm due to increase drag and lift loss due to external store carriage.

7.6. Bomber Efficiency Comparisons

The Payload – Range diagrams (payload not released) for the three bombers analysed are compared in **Fig.7.5.1**. We can initially compare the bomber efficiency by establishing PRE levels achieved for payload / range combinations (payload not released). These are shown in the following table.

Payload	Range	B-1B	B-52	B-2A
40,000	3000	975	1850	1830
	6000	N/A	1750	1650
75,000	3000	~1600	3075	N/A
	6000	N/A	2900	N/A
100,000	3000	(~2000)	N/A	N/A

From this very brief assessment, we can see that the B-52 is the most fuel efficient aircraft. However, it is surpassed by both the B-1B and the B-2A in "stealth" capability.

We note that the B-1B can carry up to 133,800 lb of payload (75,000 lb internally and 58800 lb externally). The maximum payload capacity of the B-52 may possibly be increased but not to the same extent. The B-2A is not designed for external store carriage.

Extend to BPRE estimates (To Be Possibly Added)#

Further comparisons may be made for operations involving AAR. Conventionally the military have used AAR to extend the range and duration of combat aircraft. It has been shown, Refs.4-5, that AAR used in civil aviation can greatly improve fuel efficiency.##

Payload Released, AAR option.

We can begin to explore what may ultimately become a very large matrix of options. We select a target range of 10,000 nm and assess the fuel used by each bomber to transport varying payloads to the target, release the payload and return to base. After release WP = 0. None of the bombers considered can complete a range of 10,000 nm without AAR. For this comparison we assume that tankers are operating from base and from an outstation at 6000 nm from base, **Fig.7.5.2**. This gives three AAR locations (A, B and C). The mission is broken down into seven stages as shown. Depending upon options selected and bomber payload – range capability, two or more stages may be combined.

Three basic options arise:

(1) Flying "heavy". The bombers take-off with payload and maximum fuel (At payloads greater than WPB the bomber would be above MTOW – cases omitted). The bombers refuel, out and back, at every available rendezvous (except A). At each rendezvous the tanker offloads fuel to bring the bomber up to its maximum fuel capacity.

(2) Flying "light". The bombers take-off with payload, reserve fuel and sufficient block fuel to complete Stage 1 only, arriving at rendezvous A with only reserve fuel. Tanker, T1, offloads minimum fuel for the bomber to complete Stage 2. This is repeated for stages 3 to 7, refuelling at B-C-C-B.

(3) Flying “heavy”- best Range. The bombers take-off with payload and maximum fuel (At payloads above WPB the bomber will be at MTOW). The bombers fly as far as possible before refuelling at the next available rendezvous. At each rendezvous the tanker offloads fuel to bring the bomber up to its maximum capacity.

The maximum offload required by any of the bombers, in any of the above scenarios, is just over 180,000 lb (B-1B flying “Heavy” with 60,000 lb payload). At 2000 nm radius of operation, this is on the limit of the KC-10A capability, Section 5.6. Under these conditions the Offload to WFB(Tanker) ratio is approximately 1.0. At smaller offloads the ratio decreases implying that the tanker burns more fuel than it offloads. For the present comparison, it is assumed that only KC-10A tankers are available and that the Offload to WFB(Tanker) ratio remains at 1.0. Further work could look at the optimisation of tanker type and tanker operation for particular bomber missions.

Mode of operation comparisons.

The variation of Total Mission Fuel (Bomber and Tanker) with Payload delivered at 10,000 nm radius is shown in **Fig.7.5.3**. At 4000 nm, the B-1B is close to its range limit for payloads of 20,000 to 60,000 lb. The B-1B will have to refuel at 4000 nm steps and so there is little advantage for this aircraft taking-off “Light”. Hence, only the “Heavy” line is shown for the B-1B in **Fig.7.5.3**.

For each bomber considered, payload is a very small fraction of the overall aircraft weight and so any variation in payload has little effect on total mission fuel. There are significant fuel savings if the B-52 and B-2A operate “Light”. The B-52 mission uses 25% less fuel, with 20,000 lb payload, if the bomber flies with only minimum fuel onboard. With 40,000 lb and 60,000 lb payloads the savings are 24% and 22%. The B-2A would save 19% and 16% mission fuel at 20,000 lb and 40,000 lb payload respectively. In these cases, the bombers are reliant upon pin-point accuracy during the AAR rendezvous.

Bomber comparisons.

Total Mission Fuel as a percentage of B-1B Total Mission Fuel is shown in **Fig.7.5.4** for the B-52 and B-2A at various payloads. For payloads of 20,000 lb to 60,000 lb, the B-52 uses only 67% of B-1B Mission Fuel if it operates at maximum fuel capacity. If it carries only minimum fuel, it uses approximately 50% of the B-1B mission fuel. Flying “Heavy”, the B-2A shows slightly better advantages for payloads up to 40,000 lb. Flying “Light”, savings for the B-2A are similar to those of the B-52.

We have taken one possible scenario and considered one tanker for AAR operations. We have shown that savings in total mission fuel are almost independent of payload delivered. The way in which the bombers are operated has a significant effect upon mission fuel savings. Further savings could be achieved by optimising availability of more appropriate tankers. This requires further analysis.

For improving, it will be useful to have more comprehensive data for each of the bombers. Effect of altitude, speed and aircraft configuration (e.g. External store carriage, wing sweep etc. on sfc, L/D and range).

8. OPERATIONAL EFFICIENCY AND RANGE IMPROVEMENTS

In this section we look at ways of improving fuel efficiency using existing aircraft. The design of next generation unmanned air vehicles considers the possibility of Air-to-Air Refuelling and Close Formation Flying or Swarming to increase Range and Endurance. Specific examples are used.

8.1. Payload Variations

Peak Efficiency occurs at Point A (maximum Payload), Ref.3. It was noted in Ref.2 that the efficiency of transport operations can be maximised when utilising aircraft at or near maximum payload. This can also be applied to tankers and bombers.

8.2. Air-to-Air Refuelling (AAR)

Long range bombing missions (B-1B, B-2A and B-52) and long range supply missions (C-5, C-17 and C-130) use AAR as a matter of course. Operational efficiency is improved if, in various cases, the aircraft depart with reserve fuel only on board and then refuel immediately after take-off. This would allow greater payloads to be carried (Point A operation).

Time spent “on station” by the tanker is costly in terms of fuel burnt by the tanker. It is an essential asset for fighters on combat missions. Bombers, Transports and Surveillance aircraft on long range or long endurance pre-planned missions can be refuelled by tankers on carefully planned operations with zero time “on station”. In this case, efficiency will be optimised by matching the offload required to a suitable tanker.

8.3. Close Formation Flying (CFF)

This operation is a possibility where large fleets of transport aircraft are used for supply. Similarly, large scale bombing missions (possibly unlikely in the future) could be coordinated to take advantage of CFF. AAR has already been used to facilitate these operations.

It needs to be established as a routine operation. Under hostile conditions there is insufficient time to plan and arrange coordinated re-supply chains with CFF in mind. Field commanders will need equipment and supplies delivered to specified locations without delay.

8.4. Non-Operational Procedures

Flight crew training missions are frequently flown without payload. The majority of familiarisation, conversion and refresher training flights could be assimilated into routine transport and tanking missions.

9. FIELD PERFORMANCE - TRUE COST OF STOL

We have considered Take-Off Field Length performance in some detail for the Bombers, Tankers and Surveillance aircraft in each of the relevant sections. In general, these considered conventional aircraft designs. We need to assess the penalties incurred when aircraft are designed or adapted for short field length performance.

Several interesting details are noted and can be introduced as parameters in the evaluation of field length metrics:

The C-17 can use in-flight thrust reversing to reduced Landing field length requirements
The C-135A uses water injection to increase thrust during take-off run
The F-111 and B-1 utilise variable sweep to enhance short field length performance
The Harrier uses thrust vectoring and water injection for VSTOL capability
Blown flap design

Other aircraft design and performance factors may have adverse effects on field length:

Stealth
Supersonic capability

10. FURTHER WORK

So far, we have been concerned with Phase 1-3 studies (Refs.1,2 and present).

Phase 1 involved analysis of the performance of large, subsonic, military jet transport aircraft and an assessment of where this type of aircraft lies in relation to the efficiency trends established for civil passenger aircraft. Several differences were highlighted including "g" limits operations.

The apparent anomalies in thrust to weight ratios for military and civil aircraft need further investigation. This is coupled with the need for further analysis of Take-off and Landing field length data. These factors are important in terms of operational efficiency. This would naturally extend the analysis to include STOL, VSTOL, SSTOL and VTOL type aircraft.

Phase 2 involved Military turboprop transport aircraft added to the database.

Current Phase 3 work has involved Bombers, Tankers (jet and turbo-prop) and econnaissance / Surveillance aircraft.

Selected topics (in no particular priority order) can be done, depending on the funds available.

1. Further items to include in the metrics

    UAV and UCAV

2. Hinged Wing-Tip, Take-off / cruise Improvement. The idea is that wing-tip "floats" - aerodynamic lift and supporting itself with weight of fuel). Fuel usage can be optimised. A preliminary path-finding report has been issued separately, Ref.50. However, the subject has opened out encouragingly in several directions and lot more can be done.

3. Morphing Aircraft

    Planform Morphing – speed variation
    Optimise Camber for Altitude
    Structural Morphing – Bats & Birds
    Morphing for Stability and Control

4. Effect of Reserve Fuel On Metrics

    Assess the effect of alternative fuels
    possible alternative reserve fuels (liquid hydrogen). Engine Cycle Implications.

5. Formation flying, Smart Refuelling

    Localised Tanker Networks
    Long-Range Mobility, Scheduling
    Combined Mobility Modes, Tanker + Formation Flying, Different Schemes

6. Laminar Flow e.g. on Sensor-Craft

    Passive or Hybrid or Natural (including Distributed Roughness)
    Camber changes required to fly up to CL 1.2, maintain Favourable Pressure gradient
    Performance benefits, CL – CD effects & Range
    Assuming 60% chord at 1 million leads to smaller aircraft
    Trade-offs at Loiter, Reconnaissance
    Military (Effective or Efficiency Balance)

7. Field Length Metrics in more detail

    YC-14, YC-15
    True cost of STOL

8. Different Missions & Efficiency

Art of Optimising the Design, given a range of Possibilities and Requirements
Potential of New Designs
Utilisation rates

9. Further Ideas, subject to discussions with the technical monitors at AFRL.

Further analysis on the effects of mission restrictions such as altitude or g limits on efficiency need to be incorporated and extended.

Assess the effects of operational options (AAR and CFF) on long range transport requirements.

The effects of technological advances (materials, morphing, navigation, control and positioning, etc.) on future design of transport and military aircraft in terms of efficiency need to be assessed and taken into account.

11. CONCLUSIONS

Presently there is great emphasis on achieving efficient and optimised flight. Now that fuel costs are increasing, the need for overall energy savings is being felt in all spheres of defence and commercial aviation and budgets. The military scene includes many different types of aircraft with the objectives of fulfilling many diverse roles.

Previous Phases of the work programme have been concerned with military Jets and Turbo-Prop transport aircraft and comparisons with civil passenger and freighter aircraft.

This report has been concerned with tankers, reconnaissance and surveillance aircraft, bombers, fighter aircraft, unmanned aerial vehicles (UAV) and unmanned combat aerial vehicles (UCAV).

The sequence has been chosen to allow a logical progression from the military transports to comparable types in the tanker and surveillance roles, both jet and turbo-prop.

Comparisons between various aircraft in the tanker and surveillance roles are relatively straightforward.

Tankers

All of the tankers considered are multi-role. They are both tanker and transport aircraft and as such have varying degrees of military asset value. At this stage we have considered only the tanking capabilities.

In terms of tanker efficiency parameter (TPRE), the KC-135R is slightly superior to the KC-10A. Both are 30% to 50% more efficient (depending upon Radius of operation) than the other tankers considered. However, for 100,000 lb fuel offload at 1000 nm radius, the KC-10A requires 5500 ft field length compared to 7500 ft for the KC-135A.

Further consistent performance data are required to complete this full analysis.

Surveillance Aircraft

The surveillance aircraft considered cover a very wide range of capabilities. Some are required to loiter for long periods as command and control posts to coordinate combat aircraft and tanker operations. Others perform high altitude reconnaissance missions. Some aircraft carry large items of external surveillance equipment, whilst others have their operational payload highly integrated into the airframe. In this respect, it has been difficult to extract a payload value for each type. However, two suitable metrics have been established which will allow appropriate comparisons to be made once more comprehensive data are available.

Bombers

This classification covers a wide range of capabilities – Subsonic / Supersonic, Conventional / Stealthy, Large Heavy / Light Strike. Each bomber considered operates in a variety of modes – High-altitude Stand-off, Low-altitude High-speed Penetration, Terrain following strike, etc. One or more of these modes may be used in any one mission. Naturally consistent performance data for the bombers is difficult to establish.

Estimation of non-dimensional payload range parameter BPRE/X vs Z places the bombers on the transport aircraft trends.

Comparisons of total fuel requirements (bomber and tanker) for the four bombers considered, during missions to deliver varying payloads over a 10,000 nm Radius, resulted in some interesting conclusions. Mission fuel requirements for the three large bombers (B-1B, B-52 and B-2A) increased only slightly with increasing payload (4%-5% increase when payload trebled).

The mode of operation had a significant effect. If the B-52 operates "heavy" (fuelled to maximum capacity at each stage), total mission fuel is 34% more than if it operates "light" (sufficient fuel only to complete next stage). This factor is 25% for the B-2A. In this particular scenario the B-1B had to operate "heavy" to complete the sectors between AAR rendezvous.

For the particular mission considered the B-1B requires twice as much fuel as the B-52H operating "light".

For a 20,000 lb payload, the F-111F fuel requirement is 50% that of the B-52H operating "heavy". However, the F-111F would require nine tanking operations compared to the four of the B-52H. Two F-111Fs would be required to deliver 40,000 lb payload at 10,000 nm radius and their total fuel requirements are similar to those of one B-52H carrying the same payload. Three F-111Fs would be only slightly more fuel efficient than a single B-1B delivering 60,000 lb payload.

The next stage in this analysis is to further consider field length parameters within similar missions. Naturally the take-off field length requirements for three F-111Fs would be less than that of a single B-1B when delivering 60,000 lb payload.

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Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the European Office of Aerospace Research and Development, Air Force Office of Scientific Research, Air Force Research Laboratory.

REFERENCES

1. NANGIA, R.K., “Energy Efficiency of Military Aircraft & Operations (Jet Transports)”, RKN/AERO/REPORT/2008-30, January 2008.
2. NANGIA, R.K., “Energy Efficiency of Military Aircraft & Operations (Turbo-prop Aircraft)”, RKN/AERO/REPORT/2008-40, July 2008.
3. NANGIA, R.K., “Efficiency Parameters for Modern Commercial Aircraft”, RAeS Aeronautical Journal, Volume 110, no 1110, pp 495-510, August 2006
4. NANGIA, R.K., “Operations and Aircraft Design Towards “Greener” Civil aviation Using Air-to-Air Refuelling”, RAeS Aeronautical Journal, Volume 110, No. 1113, pp. 705-721, November 2006.
5. NANGIA, R.K., "Greener” Civil Aviation Using Air-to-Air Refuelling - Relating Aircraft Design Efficiency & Tanker Offload Efficiency”, RAeS Aeronautical Journal, Vol. 111, No. 1123, pp. 589-592, September 2007.
6. NANGIA, R.K., PALMER, M.E., “Morphing UCAV wings, Incorporating in-Plane & Fold-Tip Types – Aerodynamic Design Studies”, AIAA-2006-2835. 25th Applied Aero Conference, San Francisco, June 2006.
7. NANGIA, R.K., PALMER, M.E. & DOE, R.H., “ Aerodynamic Design Studies of Conventional & Unconventional Wings with winglets”, AIAA-2006-3460. 25th Applied Aero Conference, San Francisco, June 2006.
8. NANGIA, R.K., PALMER, M.E., “Formation Flying of Commercial Aircraft – Assessment using a New Approach - Wing Span Load & Camber Control”, Paper for AIAA, 2007-0250.
9. NANGIA, R.K. & PALMER, M.E., “Formation Flying of Commercial Aircraft – Assessment using a New Approach - Wing Span Load & Camber Control”, Paper for AIAA 45th Aerospace Sciences. Meeting, Reno, AIAA-2007-0250, January 2007.
10. NANGIA, R.K., PALMER, M.E., “Formation Flying of Commercial Aircraft – Variations in Relative Size / Spacing – Induced Effects & Control”, AIAA Paper 2007-4163, June 2007.
11. NANGIA, R.K., PALMER, M.E., “Formation Flying of Oblique Wing Aircraft - Assessment of Variations in Relative Size / Spacing – Induced Effects & Control”, Proposed Paper for AIAA, 2006-7.
12. GREEN, J.E., “Greener by Design – the Technology Challenge”, The RAeS Aeronautical Jo., Vol.106, No.1056, February 2002, Erratum, Vol 109, no 1092. Feb 2005.
13. GREEN, J.E., “Air Travel – Greener by Design. Mitigating the Environmental Impact of Aviation: Opportunities & Priorities”, The RAeS Aeronautical Jo., Vol.109, No. 1099, Sept 2005.
14. NANGIA, R.K., “Design Efficiency Parameters for Civil Freighter Aircraft”, Paper to be published.
15. KUCHEMANN, D. "The Aerodynamic Design of Aircraft", Pergamon.
16. TORENBEEK, E., “Synthesis of Subsonic Airplane Design”, Delft University Press,Netherlands, 1981.
17. Aerospace Source Book 2009, Aviation Week & Space Technology, McGraw-Hill
18. JENKINSON et al, “Civil Jet Aircraft Design”, Arnold, 1999.

19. FIELDING, J.P., “Introduction to Aircraft Design”, Cambridge University Press, 1999.
20. Jane’s Aircraft Recognition Guide, Harper Collins, 1996
21. World Aircraft Information Files, Aerospace Publishing
22. American Military Aircraft, Grange Books, 2005, Editor Winchester. J.
23. www.af.mil/factsheets
24. www.airforce-tecnology.com
25. http.//aeroweb.brooklyn.cuny.edu
26. www.simviation.com
27. www.globalsecurity.org
28. www.aerospaceweb.org
29. **www.lockheed**
30. www.airbus
31. **www.boeing**
32. “The Pocket Guide to the MRTT”, Airbus Industrie, AI/CM-PV 319.0014/96, August 1996
33. “A330 MRTT Pocket Guide”, EADS CASA, MTAD 0010 / April 2006 AGUK 6200H
34. “The Pocket Guide to A400M the Versatile Airlifter”, Airbus Military, AM/C 0068/04, March 2006
35. “KC-30 Tanker Total Air Mobility”, ISER-MLB-PR-07-17 48057 3/15/07
36. “Boeing 767 Tanker Transport”, The Boeing Company, YG-02-335-002
37. WOODS, R., SCOTT, W., et al, “B-1B Fact Book”, North American Aircraft, Rockwell International, NA-95-1210, July 1995.
38. WHITE, T. P., “KC-X Tanker Capabilities”, CAS, Inc, June 2007.
39. Flight International, 9-15 September 2008.
40. Flight International, 3-9 March 2009.
41. Air International, November 2002.
42. Air International, Vol 67 / No 1, Jul 2004.
43. Air International, Vol 71 / No 3,Sep 2006.
44. Air International, Vol 75 / No 2, Aug 2008.
45. Air International, September 2008.
46. Air International, Vol 76 / No 5, May 2009.
47. Air Forces Monthly, June 2008.
48. Combat Aircraft, Vol.9, No.4, August-September 2008.
49. BLAKE, W.B., Communication, May 2009.
50. NANGIA, R.K., “Improving Energy Efficiency of Military Aircraft & Operations, “Floating” Fuel-Carrying Wing-tips”, RKN / AERO / REPORT / 2009-60, June 2009.

LIST OF SYMBOLS AND ABBREVIATIONS

Only the general symbols are defined here. Other symbols are of local significance within the Section they arise in.

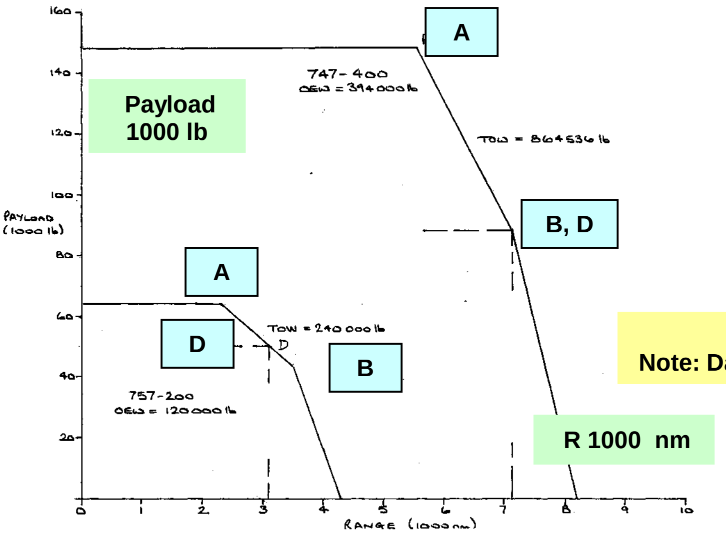
Performance Related

BPRE	PRE for Bombers = WP *Radius/WFB
c1, c2	Technology constants (see Section 4)
CFRP	Carbon Fibre Reinforced Plastic
DOC	Direct Operating Costs
EXP	Exponential
HBPR	High By-Pass Ratio Engines
L/D	Aircraft Lift/Drag Ratio
M	Mach Number
OEW	Operating Empty Weight
PRE	= WP *R/WFB, Payload Range Efficiency
Pt	Point
R	Range (nm or km)
Radius	Radius of Operation (Tankers, Surveillance and Bombers)
ROS	Range on Station – distance (nm) Tanker flies whilst on station
SFC	Specific Fuel Consumption
STOL	Short Take-Off and Landing
SSTOL	Super Short Take-Off and Landing
TOS	Time on Station (hr) for Tankers
TOW	Take-Off Weight (MTOW, Maximum)
TPRE	PRE for Tankers = Offload *Radius/WFB
V	Aircraft Velocity
VEM	= PRE/MTOW, Value efficiency per MTOW unit
VEO	= PRE/OEW, Value efficiency per OEW unit
VEMPX	= VEM*WP/X, Non-Dimensional Value Efficiency, Section 6
VEOPX	= VEO*WP/X, Non-Dimensional Value Efficiency, Section 6
VSTOL	Very Short Take-Off and Landing
VTOL	Vertical Take-Off and Landing
WFB	Block Fuel Load
WFB / WP	Fuel Payload Fraction (FPF)
WFRes	or WFR, Reserve Fuel Load
WFT	Total Fuel Load
WP	Payload
WP/WFB	Payload Efficiency
X	= V * (L/D) / SFC
Z	= R/X
ZFW	Zero Fuel Weight (MZFW, Maximum)

General

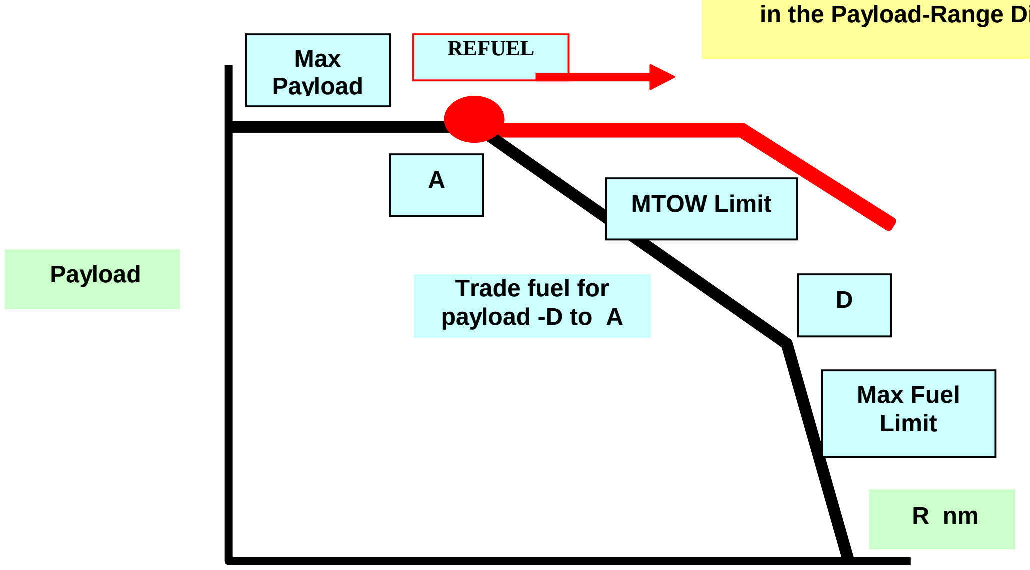
AoA	Angle of Attack (α), usually referred to the body axis
AR	Aspect Ratio
A	Axial Force along wing-plane x-axis (for definition of CA)
b	= 2 s, Wing span
BL	Boundary Layer
c	Local Wing Chord
c_{aero}	= c, Aerodynamic Wing Chord
c_{av}	= c = cref, Average Wing Chord
C_A	= A/(q S), Axial Force Coefficient, measured in Wing plane

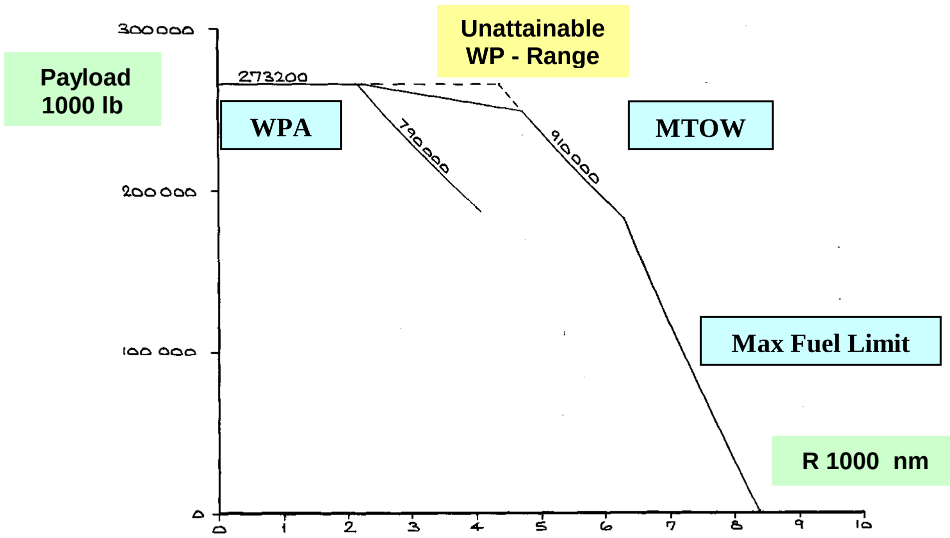
C_{AL}	= Local Axial Force Coefficient
C_D	= Drag Force /(q S), Drag Coefficient
C_{D0}	Drag Coefficient at zero lift (see text)
C_{Di}	Lift Induced Drag
CG	Centre of Gravity
C_l	= l/(q S b), Rolling Moment Coefficient (Body Axis, positive right tip up)
C_L	= CL = L/(q S), Lift Coefficient
C_{LL}	= Local Lift Coefficient
C_{Lmax}	Maximum Lift Coefficient
C_m	= m/(q S c), Pitching Moment Coefficient (Body Axis, positive nose up)
C_{mo}	Cm at zero Lift
C_n	= n/(q S b), Yawing Moment Coefficient (Body Axis)
C_N	= N/(q S), Normal Force Coefficient
CoP	Centre of Pressure
C_P	Coefficient of Pressure
c_r, c_t	Wing Root chord, Wing Tip chord
DOF	Degrees Of Freedom
k	$= \pi A C_{Di}/C_L^2$, Lift Induced Drag Factor
l	Rolling moment (Body Axis, positive right tip up)
LE	Leading Edge
m	Pitching moment (Body Axis, positive nose up)
M	Mach Number
MRC	Moment Reference Centre
n	Yawing moment (Body Axis)
N	Normal Force
Non-D	non-dimensional
q	$= 0.5 \rho V^2$, Dynamic Pressure
r	Aerofoil radius
rn	Aerofoil radius normal to c
R	Reynolds Number, based on cav (unless otherwise stated)
s	Wing semi-span
S	Wing Area, taken here as (front-wing + tip-wing) area
t	Aerofoil thickness
TE	Trailing Edge
V	Airstream Velocity
x,y,z	Orthogonal Wing Co-ordinates, x along body axis
x_{ac}	Location of Aerodynamic Centre along x-axis
x_{cp}	Location of Centre of pressure along x-axis
α	Angle of Attack (AoA), usually referred to the body axis
λ	Wing Taper Ratio
Λ	LE Sweep Angle
ρ	Air Density
η	= y/s, Non-dimensional spanwise Distance



(a) B757-200 & B747-400
Note: Data not fully consistent in all SOURCES

(b) Explaining Various Limits
in the Payload-Range Diagram





(c) B747-400ERF, Payload – Range, Showing Projected Point A and Unattainable WP- Range Region

FIG.3.1.1 TYPICAL PAYLOAD RANGE DIAGRAMS & LIMITS

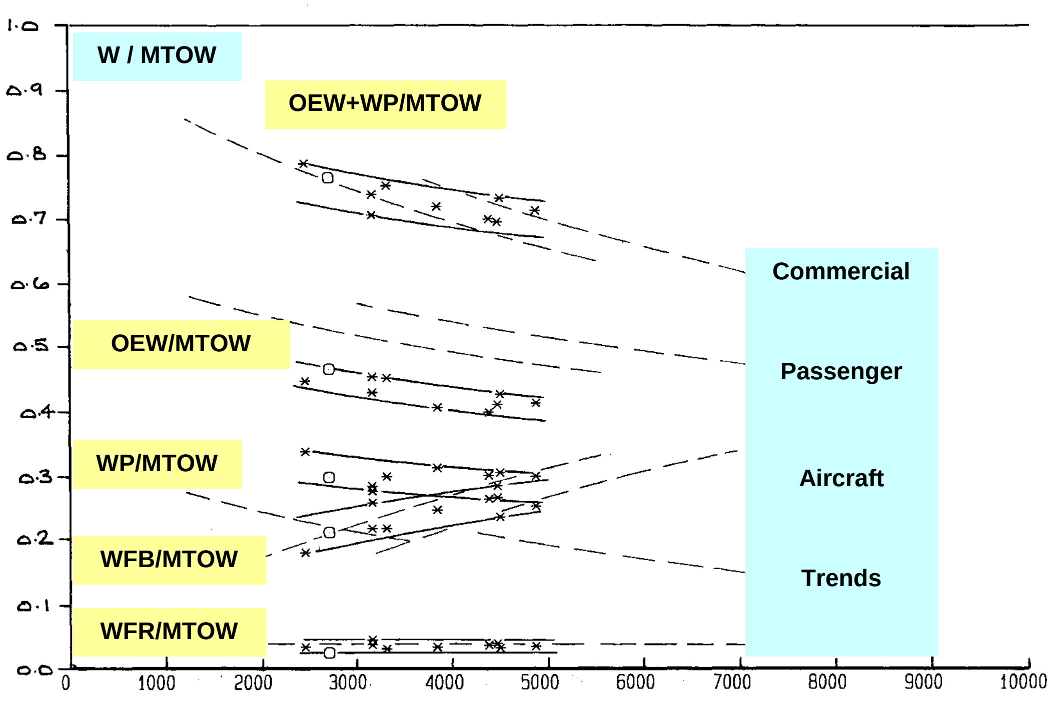


Fig. 3.4.1 Pt A, CIVIL FREIGHTER AIRCRAFT, DERIVED OEW, FUEL & PAYLOAD RATIO TRENDS, COMMERCIAL PASSENGER AIRCRAFT TRENDS

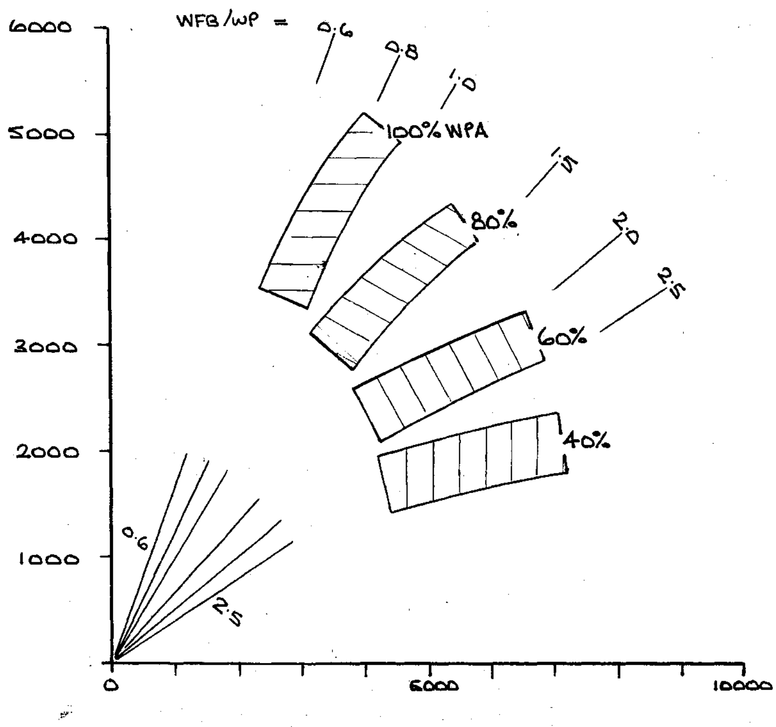


Fig. 3.4.2 PRE vs RANGE, BANDS FOR VARYING PAYLOAD FRACTION, FREIGHTER AIRCRAFT CONSTANT WFB/WP (RADIAL LINES)

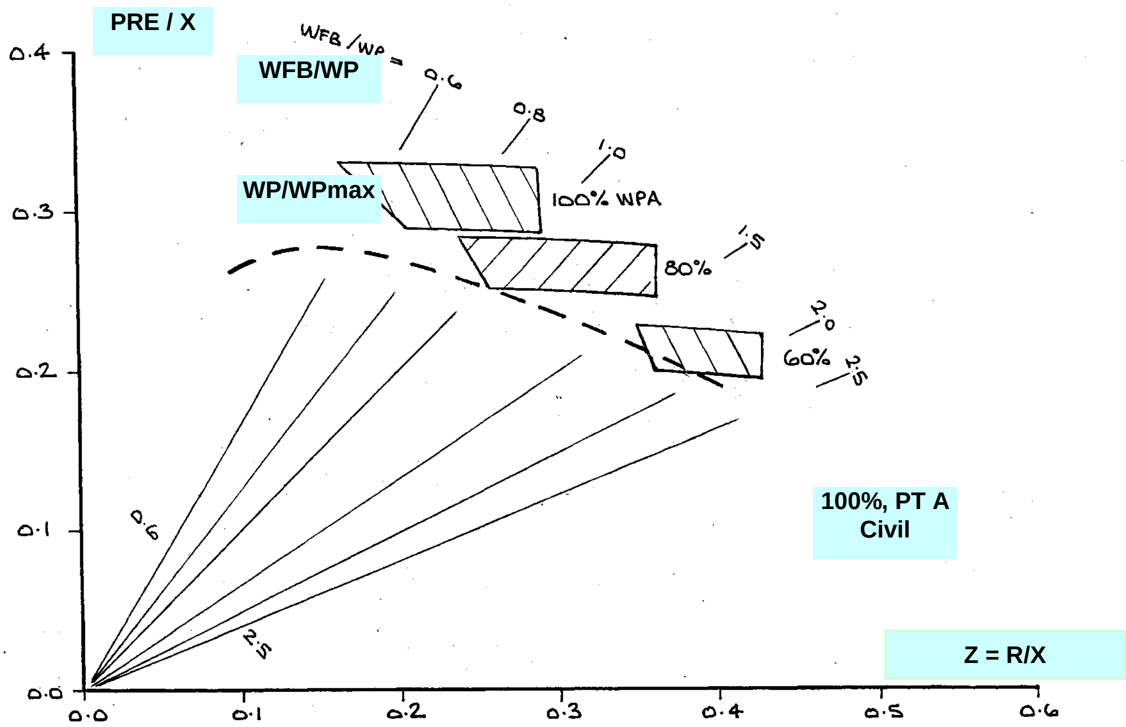


Fig. 3.4.3 PRE/X vs Z, BANDS FOR VARYING PAYLOAD FRACTION, FREIGHTER AIRCRAFT, CIVIL AIRCRAFT PT A TRENDS, CONSTANT WFB/WP (RADIAL LINES)

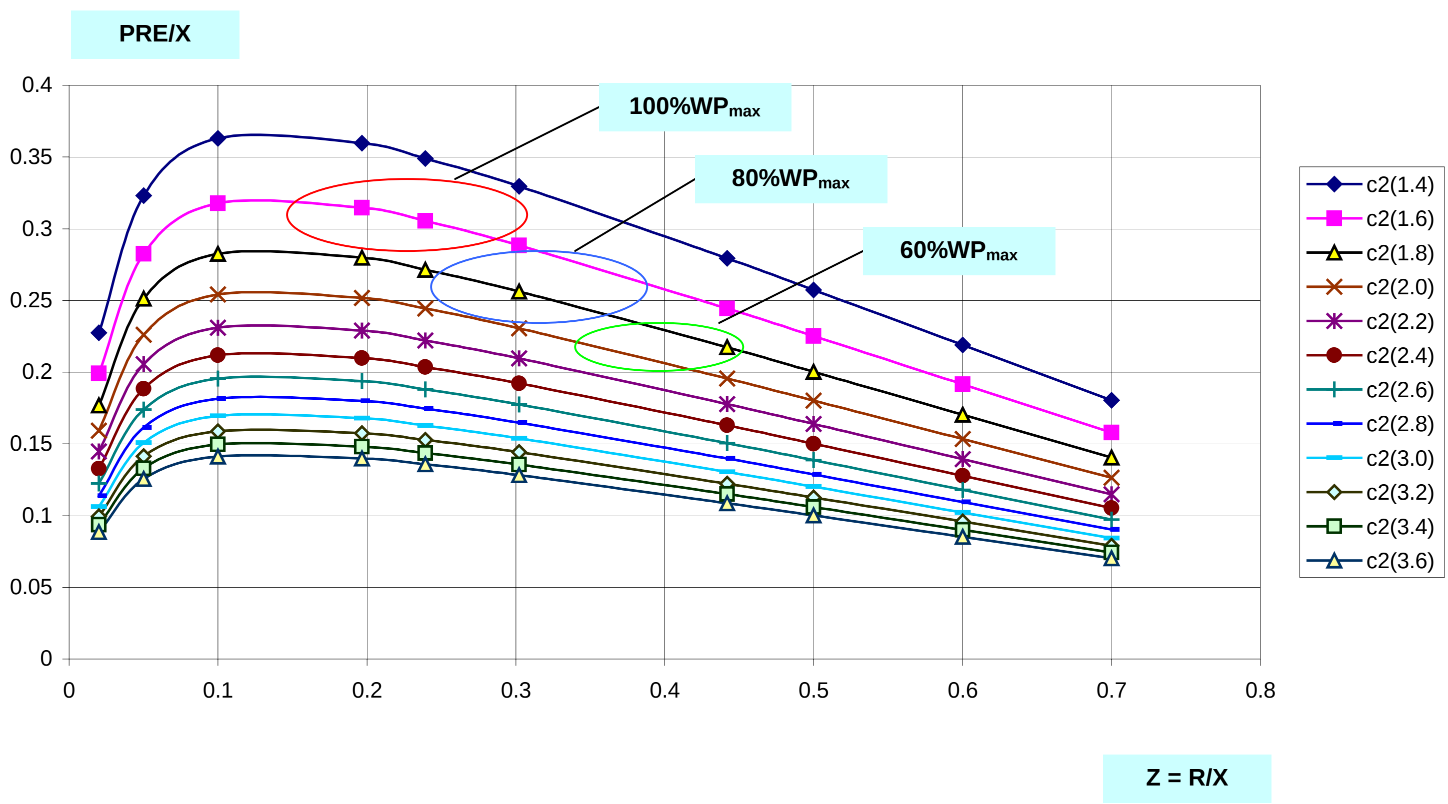


Fig. 3.4.4 PRE/X vs Z, c1 +WFR/MTOW = 0.30, c2 VARIES, BANDS FOR FREIGHTER AIRCRAFT VARYING PAYLOAD FRACTION

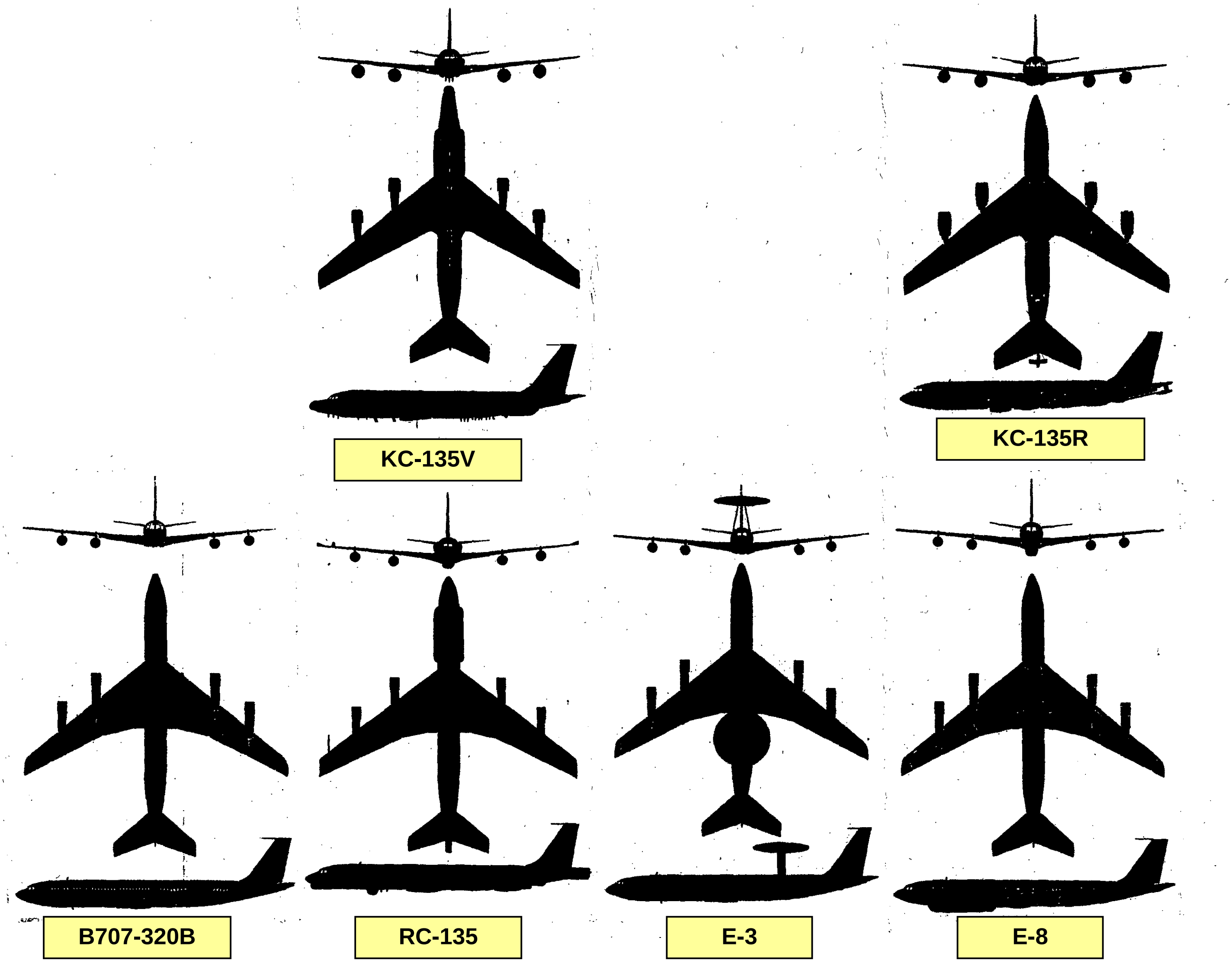


Fig. 4.1.1 BOEING 707-320B and MILITARY DERIVATIVES GEOMETRY COMPARISON

Fig. 4.1.2 E-6B
(BOEING 707-320B DERIVATIVE)

Fig. 4.1.3 737-AEW&C
(BOEING 737-200 DERIVATIVE)

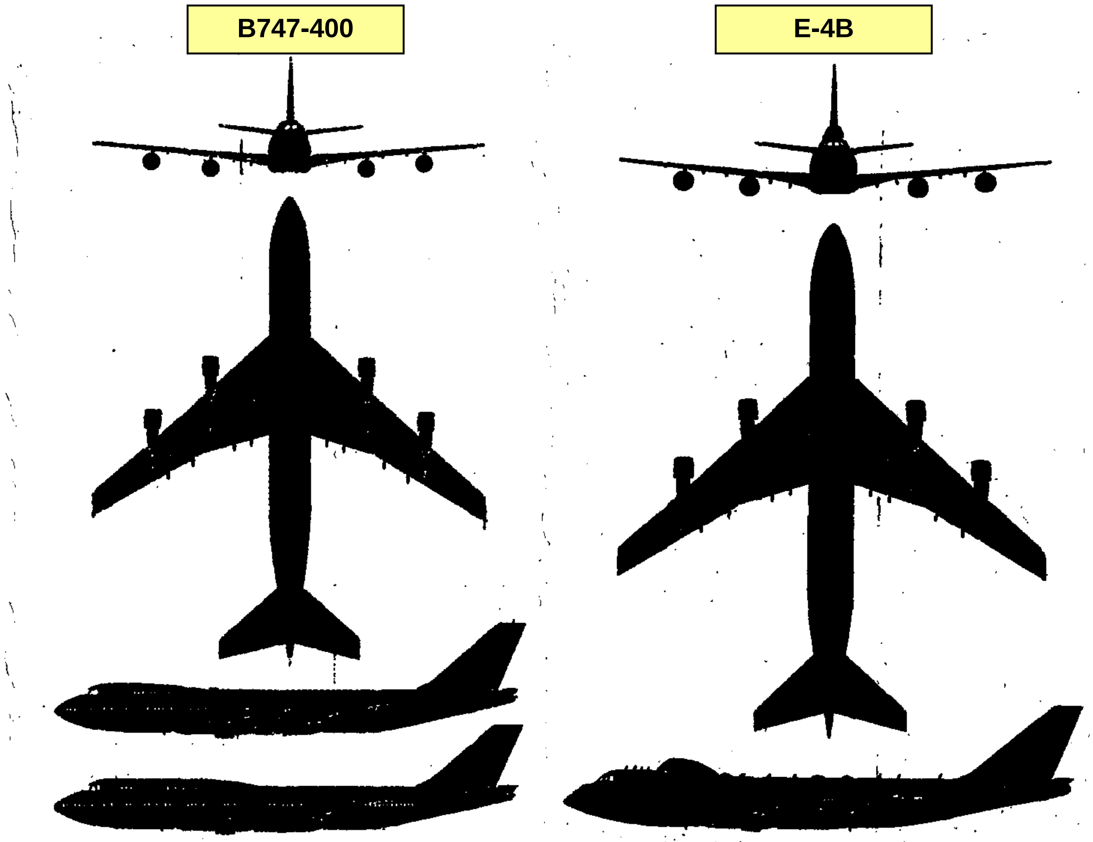


Fig. 4.1.4 BOEING 747-400 and BOEING E-4B GEOMETRY COMPARISON

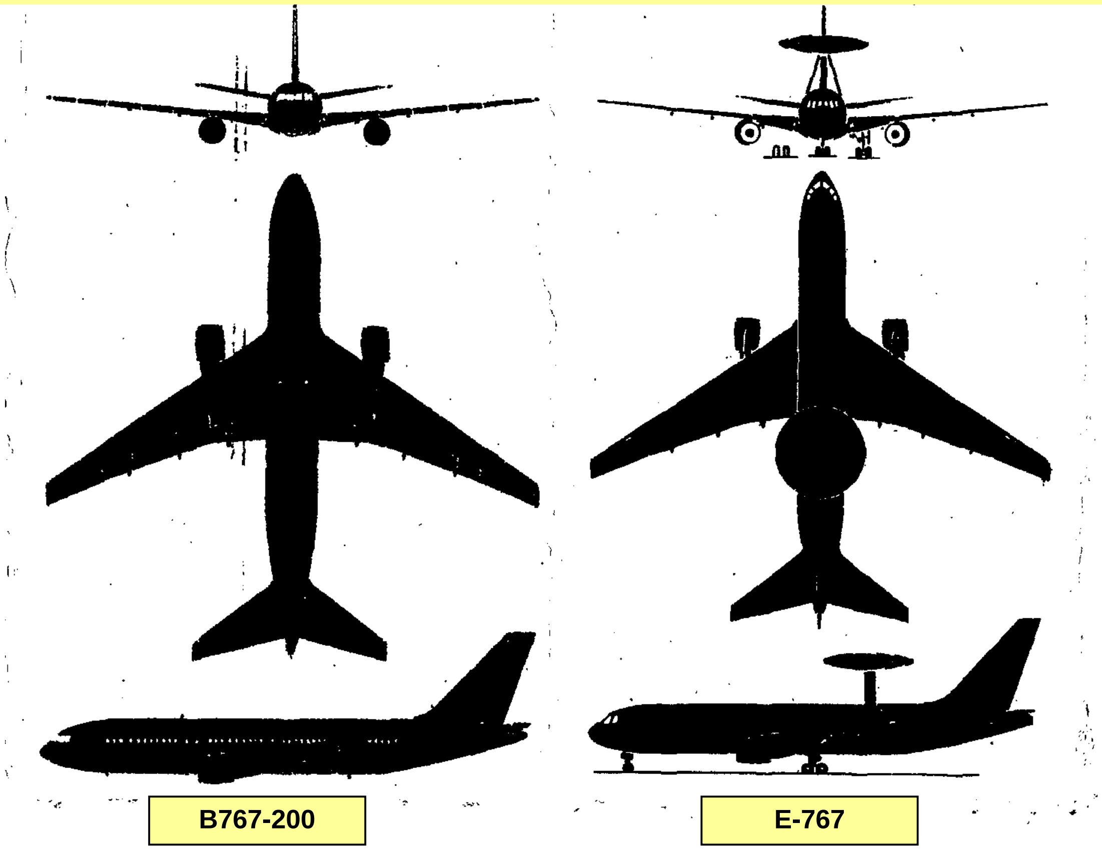


Fig. 4.1.5 BOEING 767-200 and BOEING E-767 GEOMETRY COMPARISON

Fig. 4.1.6 LOCKHEED U-2

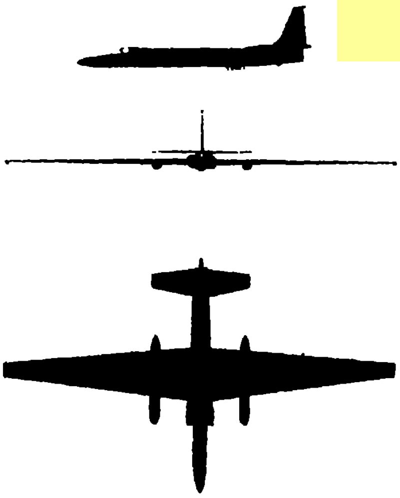


Fig. 4.1.7 NORTHROP GRUMMAN RQ-4A and RQ-4B/N (GLOBALHAWK)

Fig.4.1.8 LOCKHEED C130J HERCULES

Fig.4.1.9 AIRBUS A400M

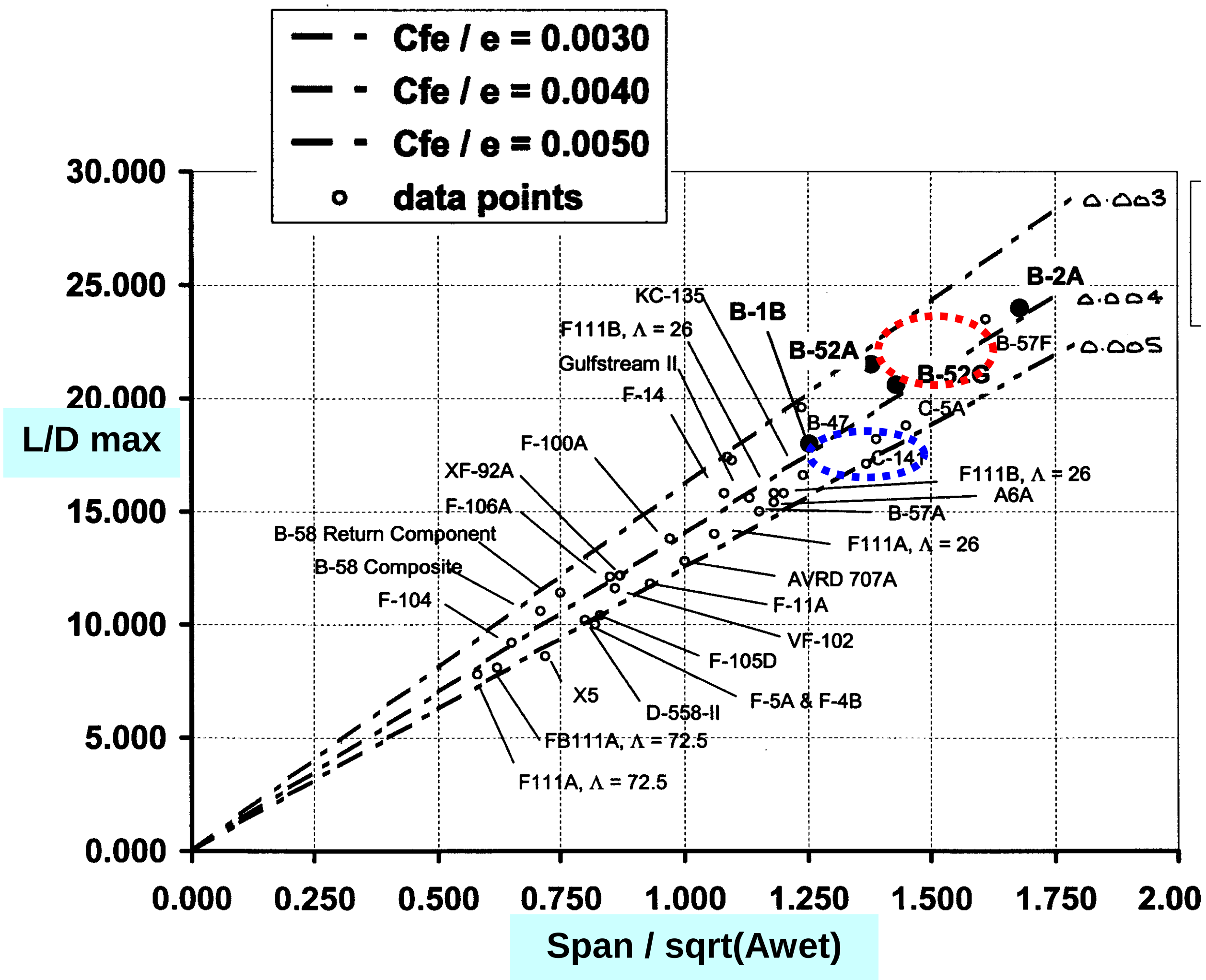


Fig. 4.3.1 SUBSONIC L/D max v NORMALISED SPAN (Wetted Area)

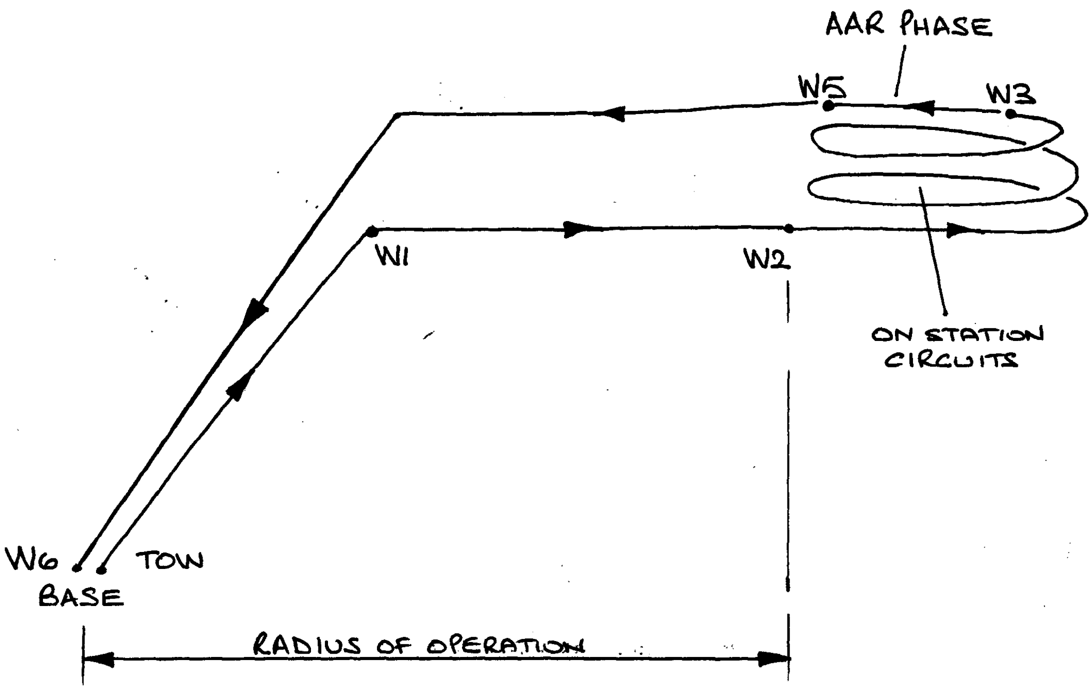


Fig. 5.1.1 SCHEMATIC SHOWING THEORETICAL APPROACH TO TYPICAL AAR OPERATION

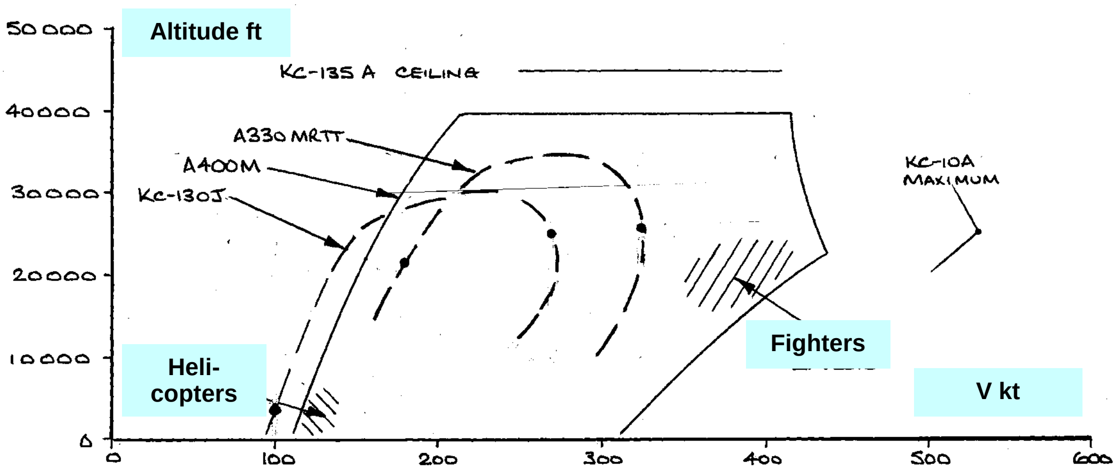


Fig. 5.1.2 NOMINAL AAR ENVELOPE, REQUIREMENTS and POSSIBILITIES

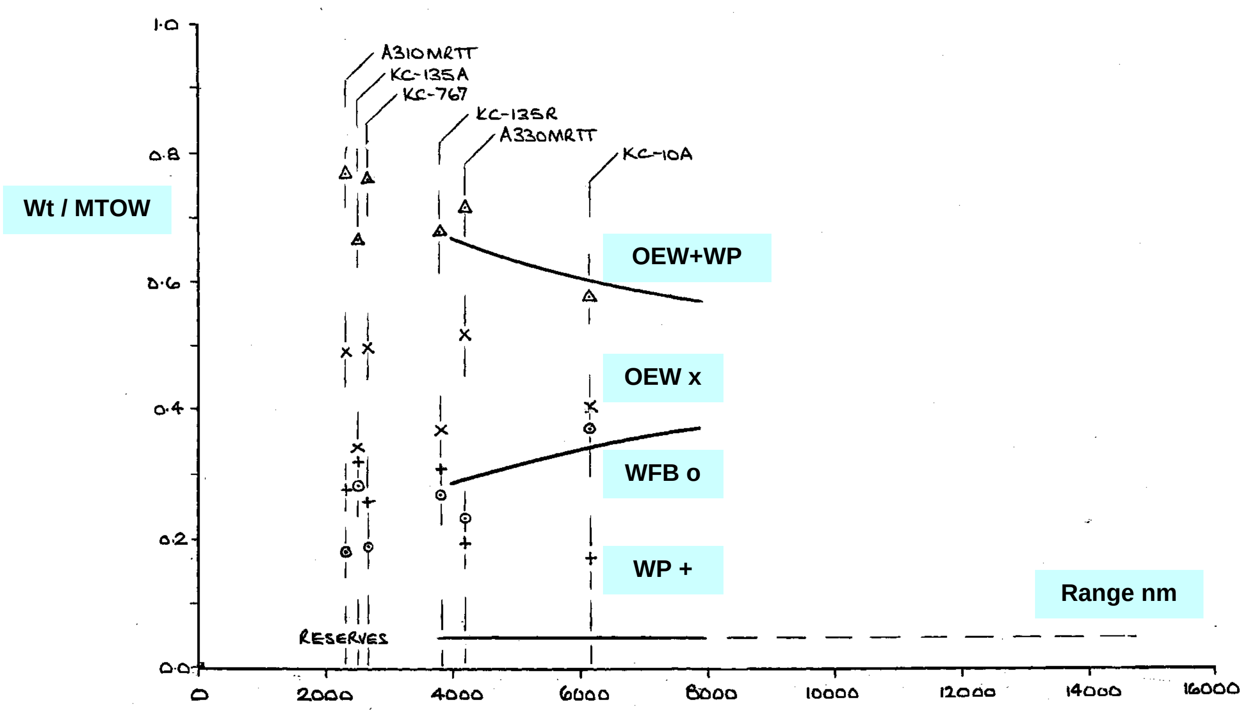


Fig. 5.1.3 TANKER, WEIGHT RATIOS wrt MTOW v POINT B RANGE,
CIVIL FREIGHTER JET AIRCRAFT TRENDS

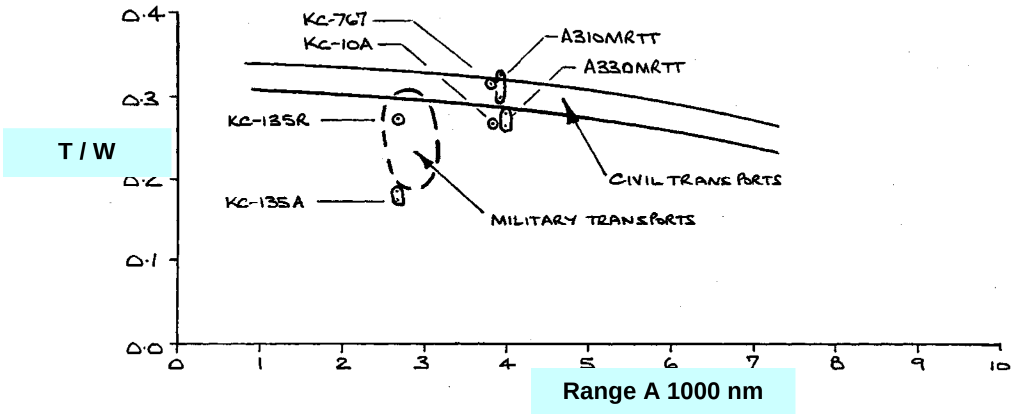


Fig. 5.1.4 TANKER, T/W - A RANGE,
CIVIL FREIGHTER JET AIRCRAFT TRENDS

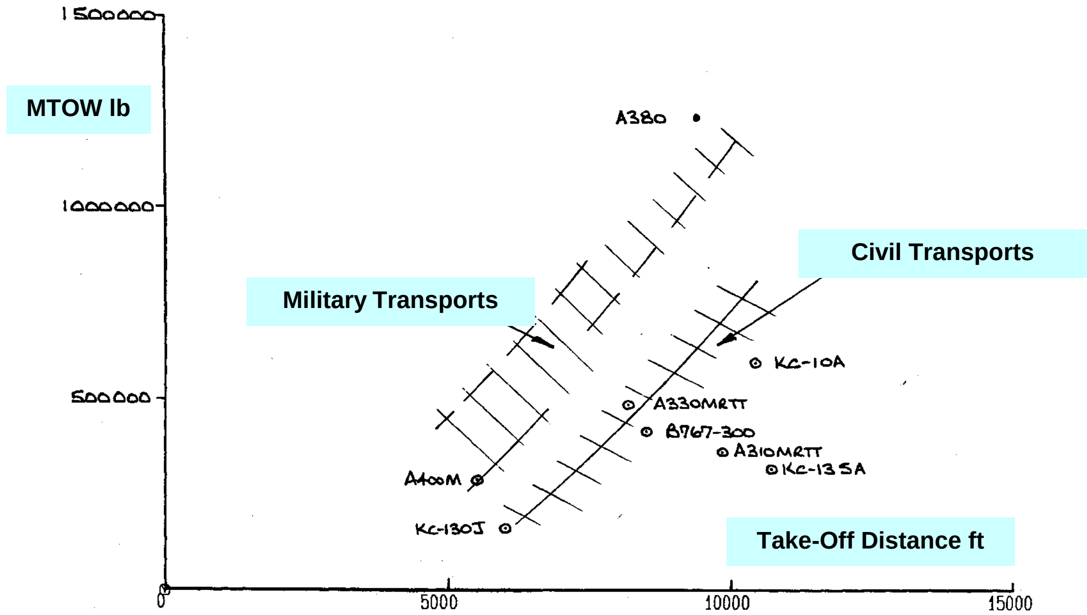


**Fig. 5.1.5 TANKER, MTOW – TAKE-OFF DISTANCE,
CIVIL and MILITARY TRANSPORT TRENDS**

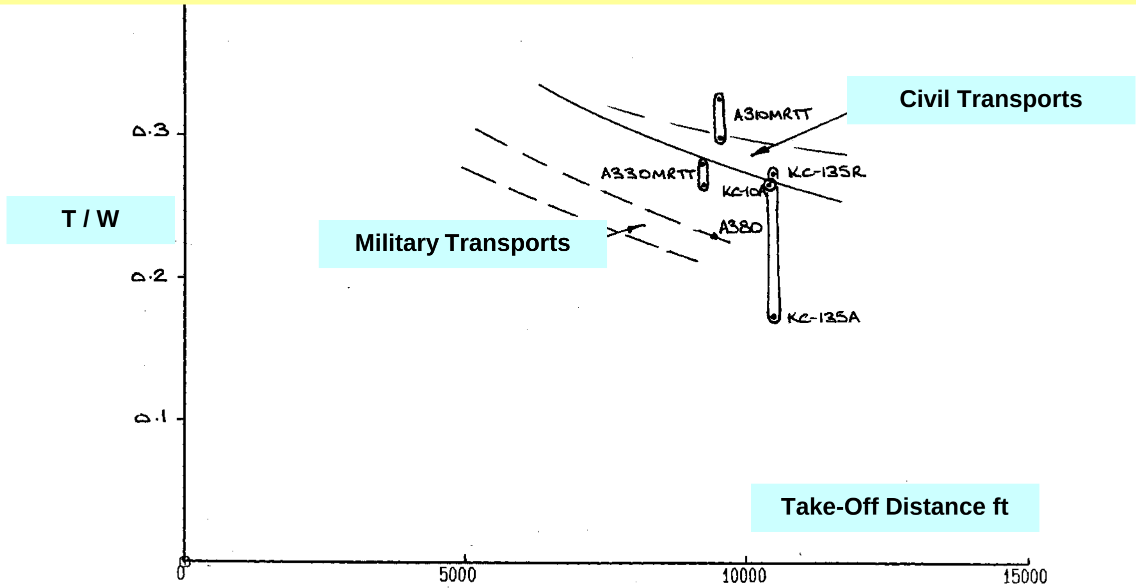


**Fig. 5.1.6 TANKER, T/W – TAKE-OFF DISTANCE,
CIVIL and MILITARY TRANSPORT TRENDS**

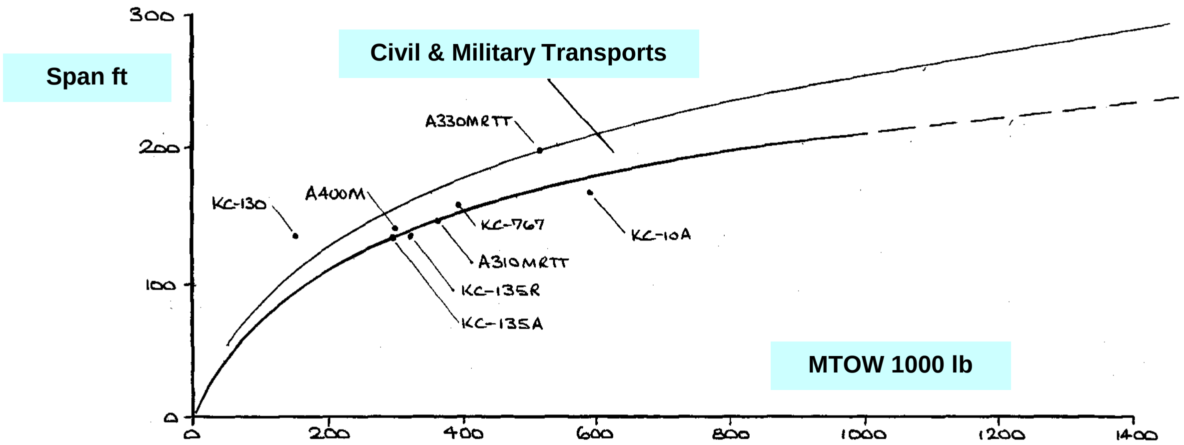


**Fig. 5.1.7 TANKER, SPAN (b ft) - MTOW,
CIVIL and MILITARY TRANSPORT TRENDS**

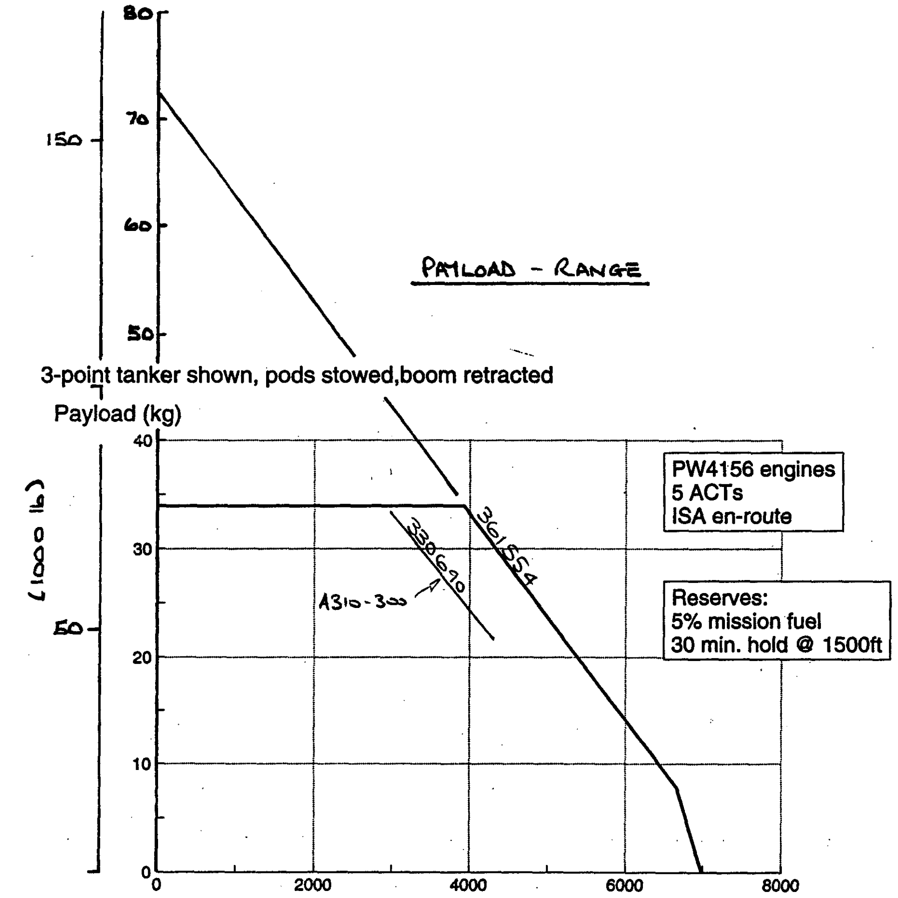


Fig. 5.2.1 A310 MRTT PAYLOAD – RANGE
cf A310-300 civil airliner

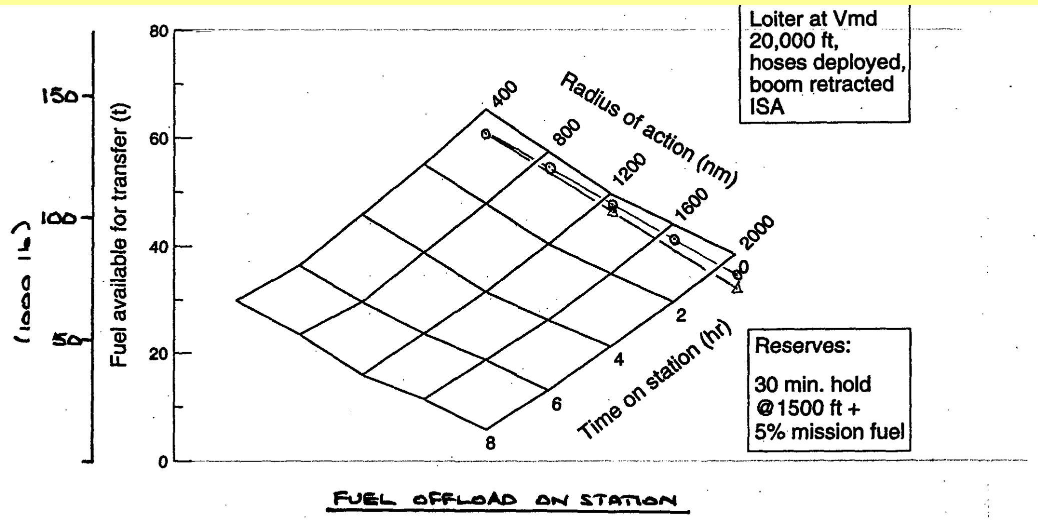


Fig. 5.2.2 A310 MRTT FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS AND TIME ON STATION
Two Hose-and-Drogue at 2000 lb/min each

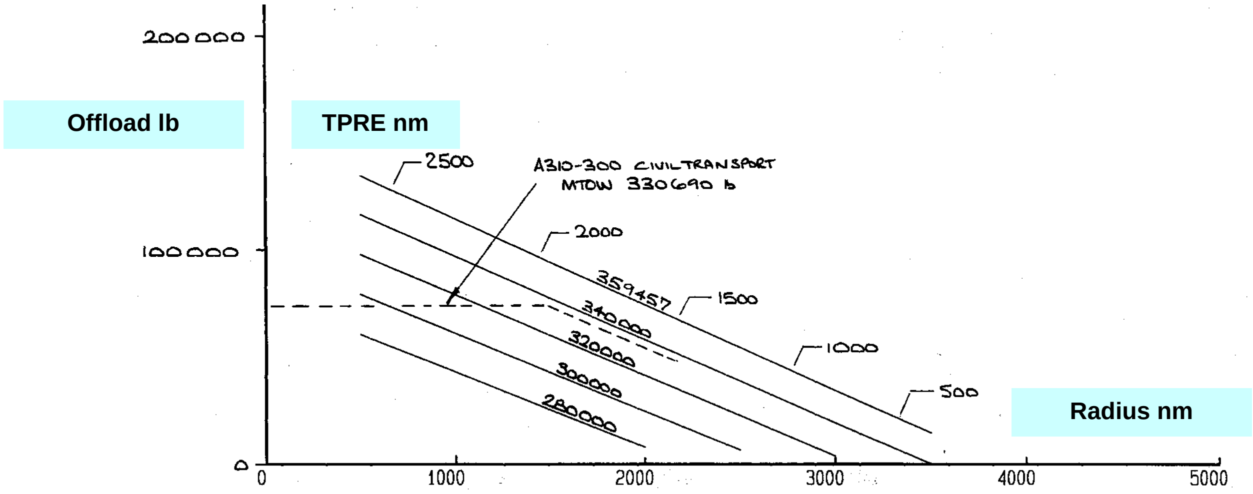


Fig. 5.2.3 A310 MRTT FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS
Boom at 8000 lb/min

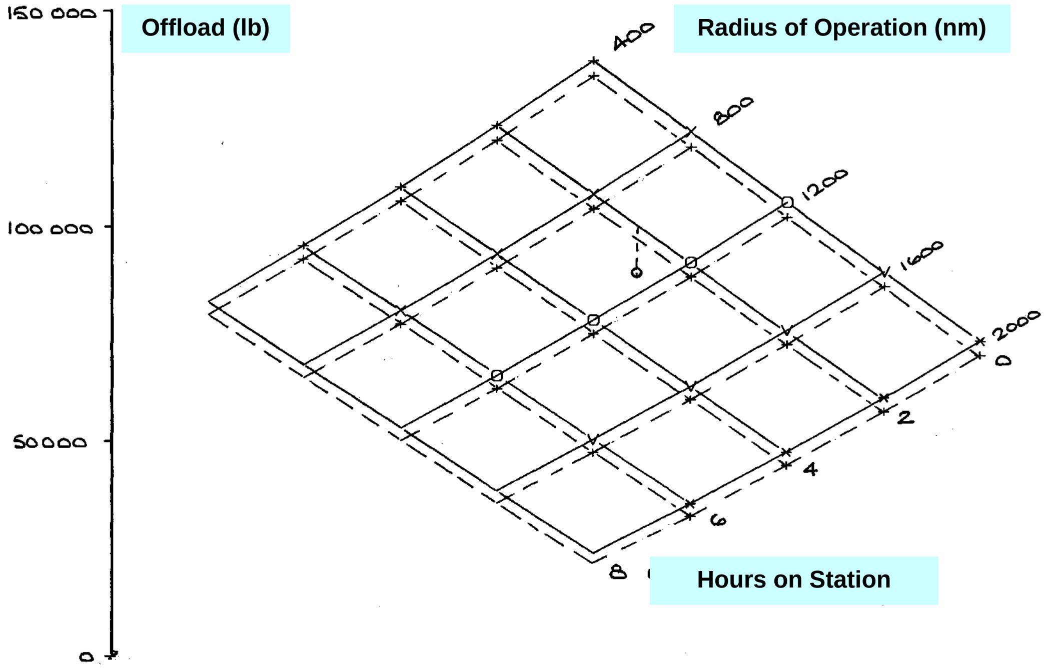


Fig. 5.2.4 A310 MRTT FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS AND TIME ON STATION
Boom 8000 lb/min (solid) & Two Hose-and-Drogue at 2000 lb/min each (dashed)

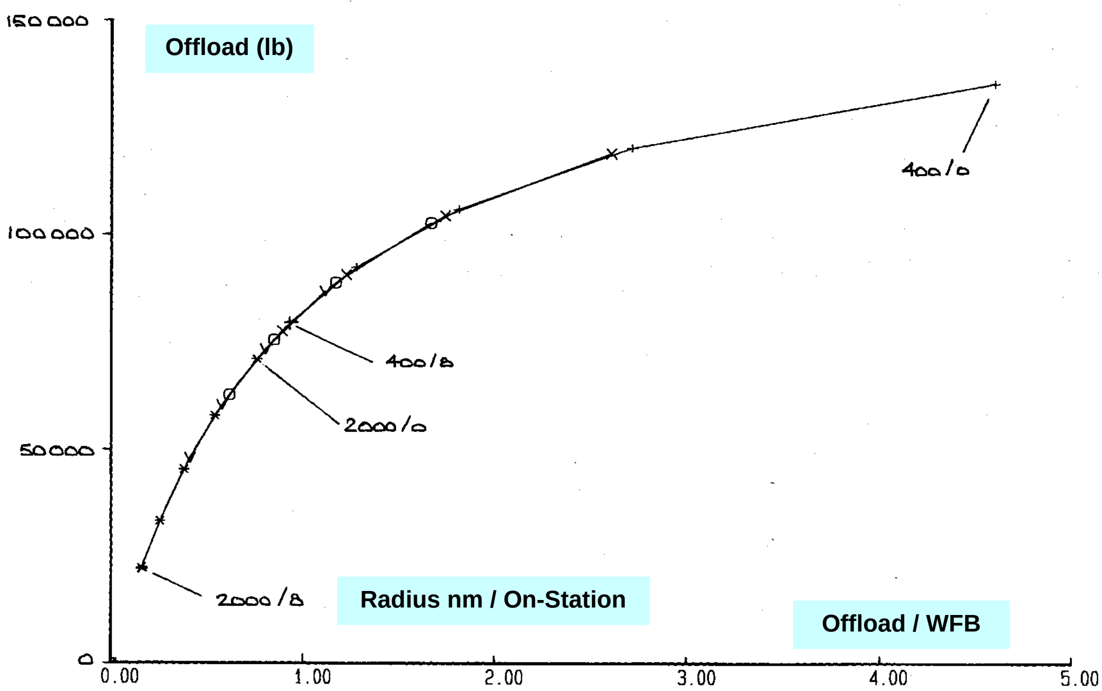


**Fig. 5.2.5 A310 MRTT FUEL OFFLOAD VARIATION WITH FUEL BURN EFFICIENCY
Two Hose-and-Drogue at 2000 lb/min each**

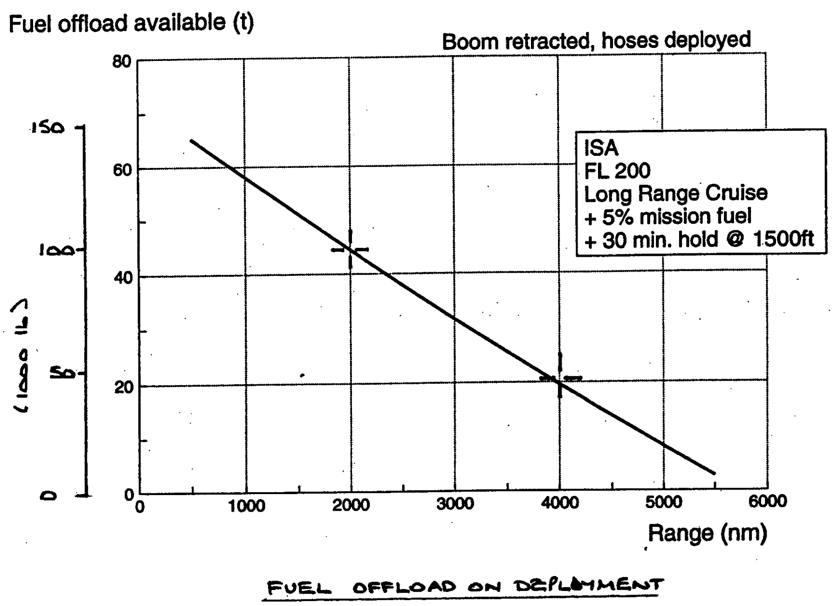


**Fig. 5.2.6 A310 MRTT VARIATION OF FUEL OFFLOAD
ON DEPLOYMENT WITH RANGE**

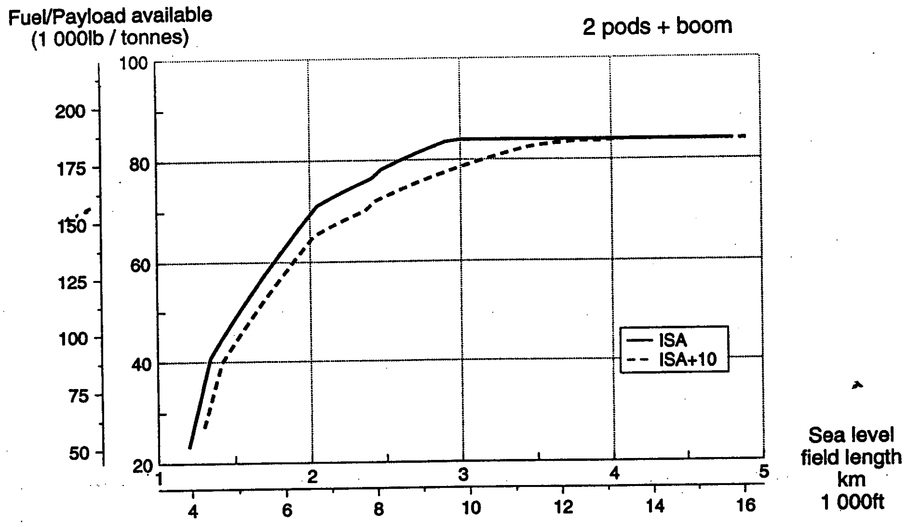


Fig. 5.2.7 A310 MRTT TAKE-OFF PERFORMANCE

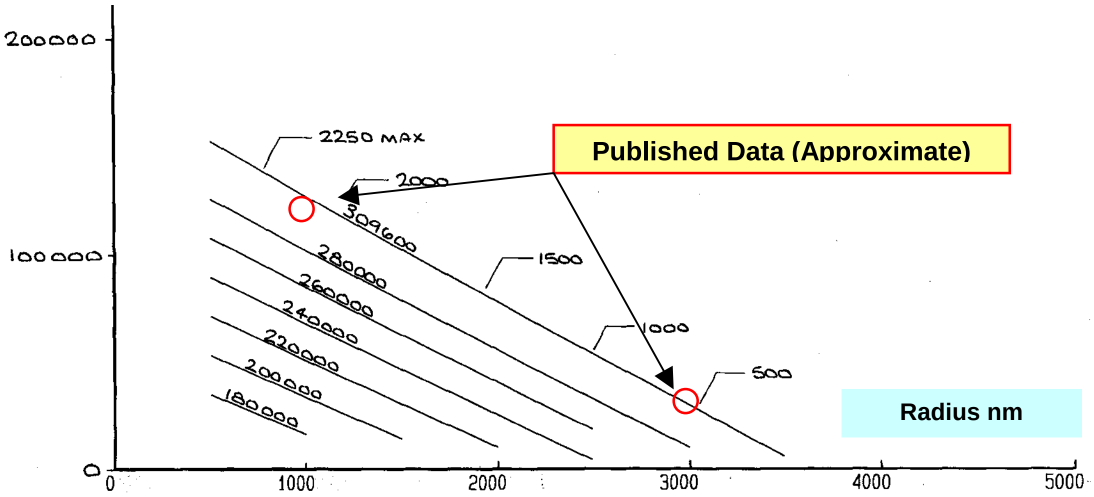


Fig. 5.3.1 KC-135A FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS
Boom at 8000 lb/min

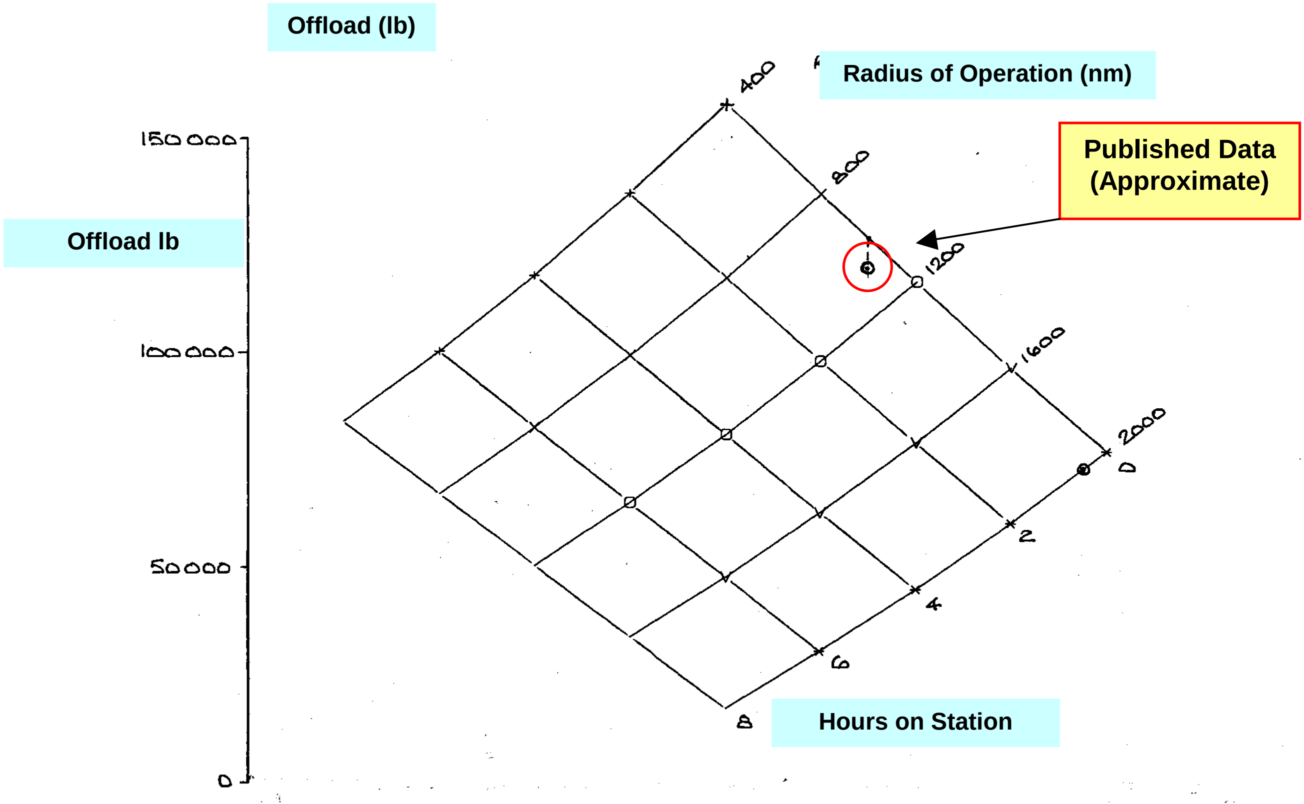


Fig. 5.3.2 KC-135A FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS AND TIME ON STATION
Single Boom at 8000 lb/min

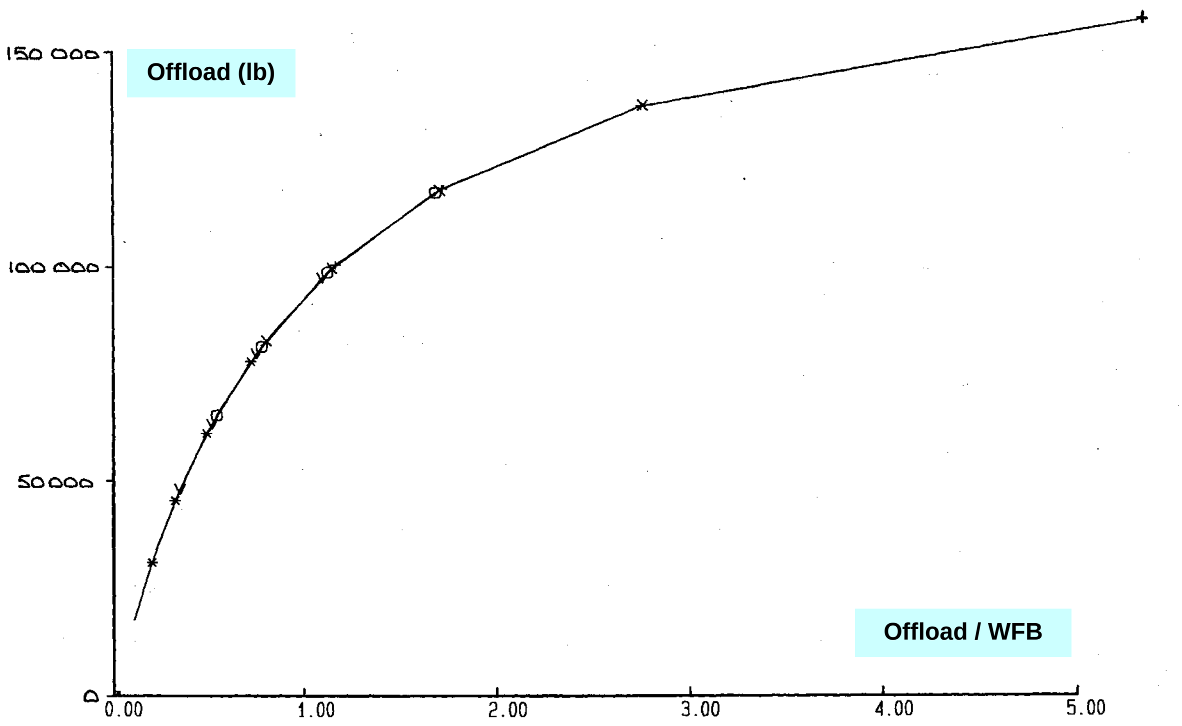


Fig. 5.3.3 KC-135A FUEL OFFLOAD VARIATION WITH FUEL BURN EFFICIENCY
Single Boom at 8000 lb/min

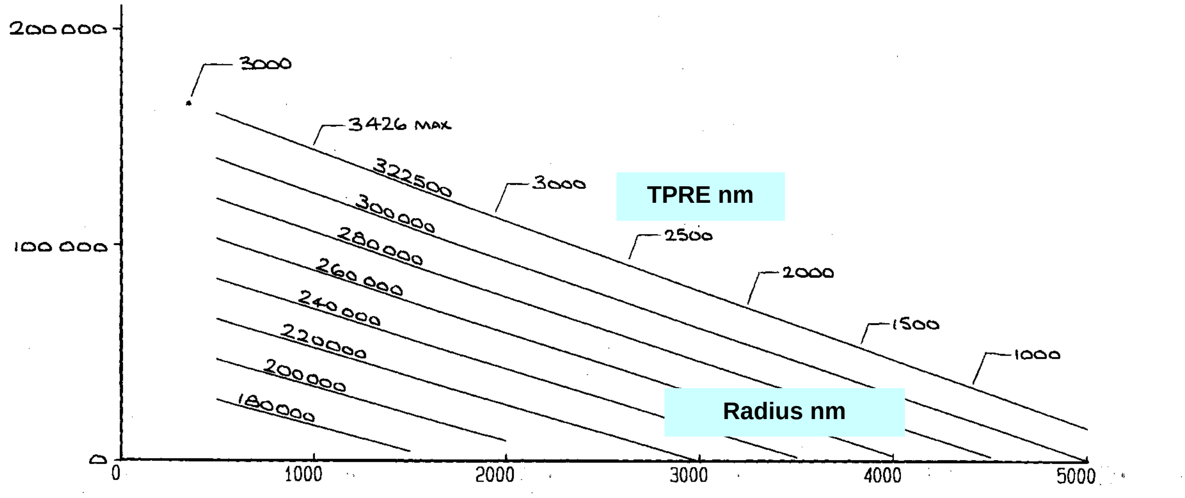


Fig. 5.3.4 KC-135R FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS
Boom at 8000 lb/min

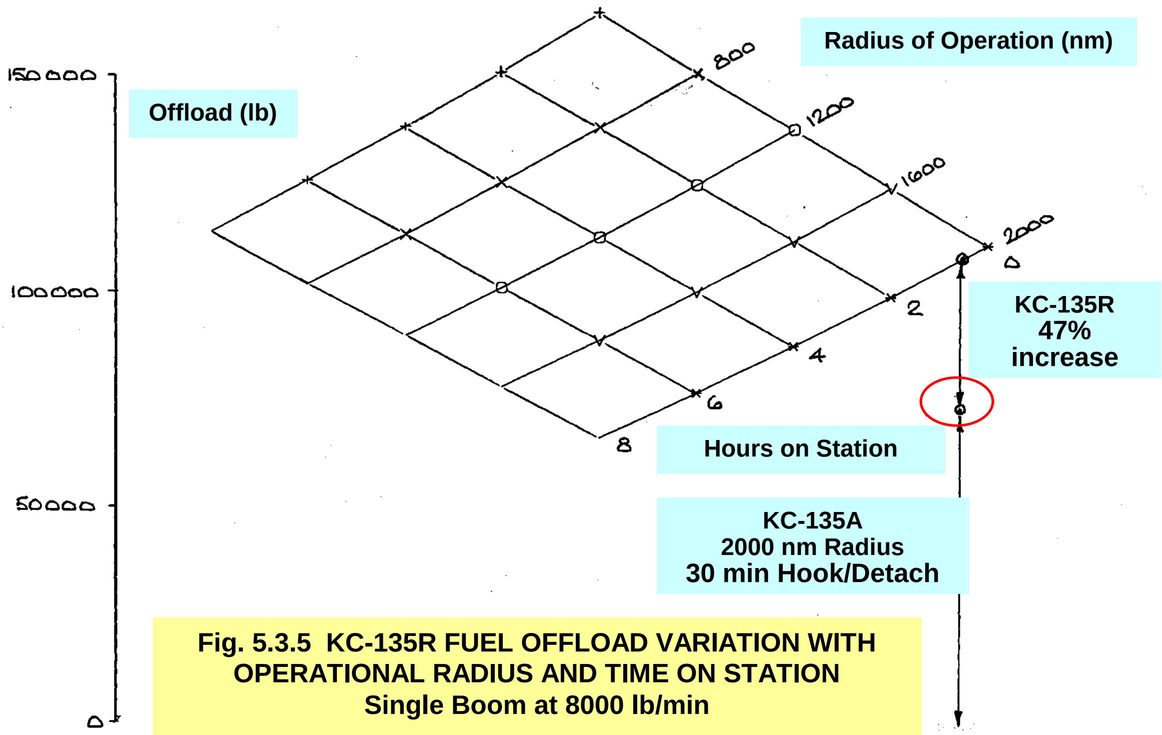


Fig. 5.3.5 KC-135R FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS AND TIME ON STATION
Single Boom at 8000 lb/min

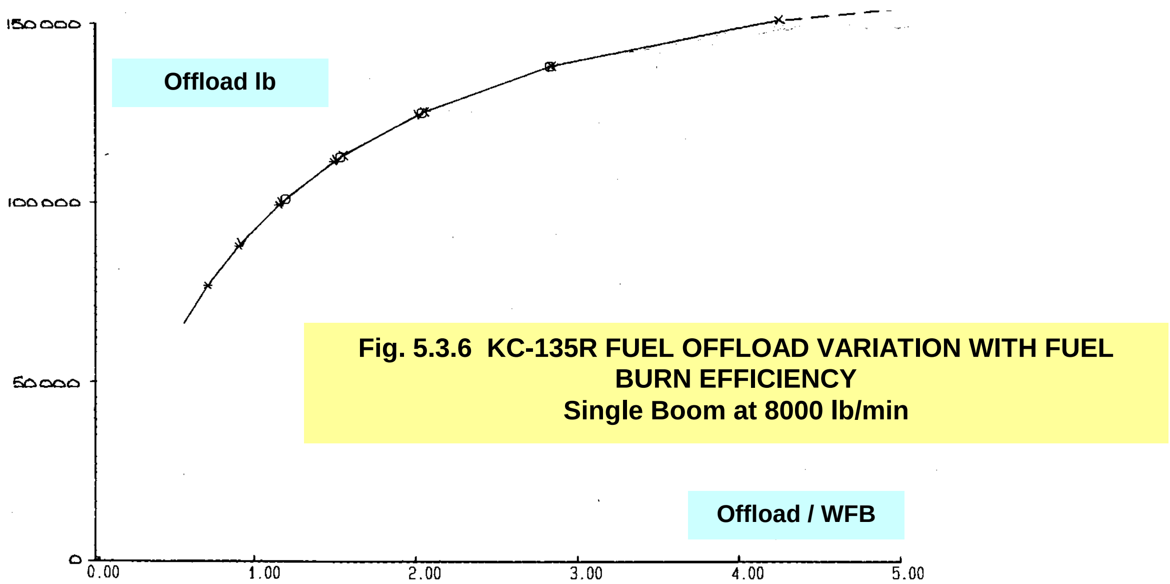


Fig. 5.3.6 KC-135R FUEL OFFLOAD VARIATION WITH FUEL BURN EFFICIENCY
Single Boom at 8000 lb/min

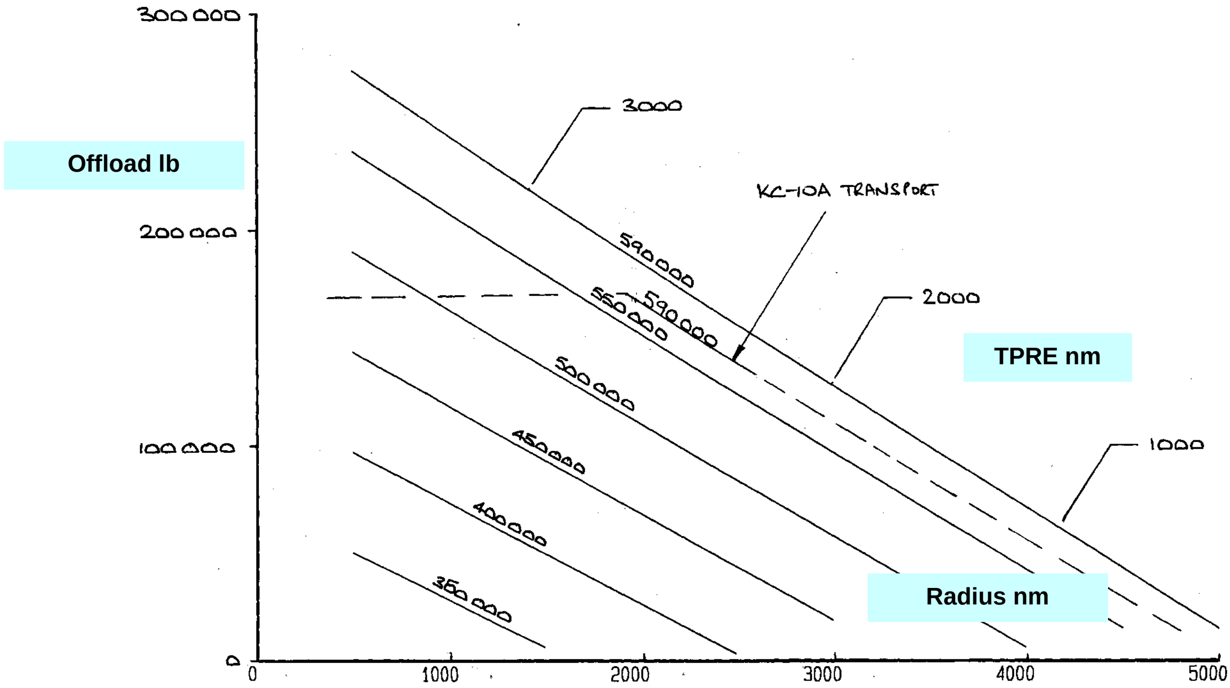


Fig. 5.4.1 KC-10A EXTENDER FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS
Boom at 8000 lb/min

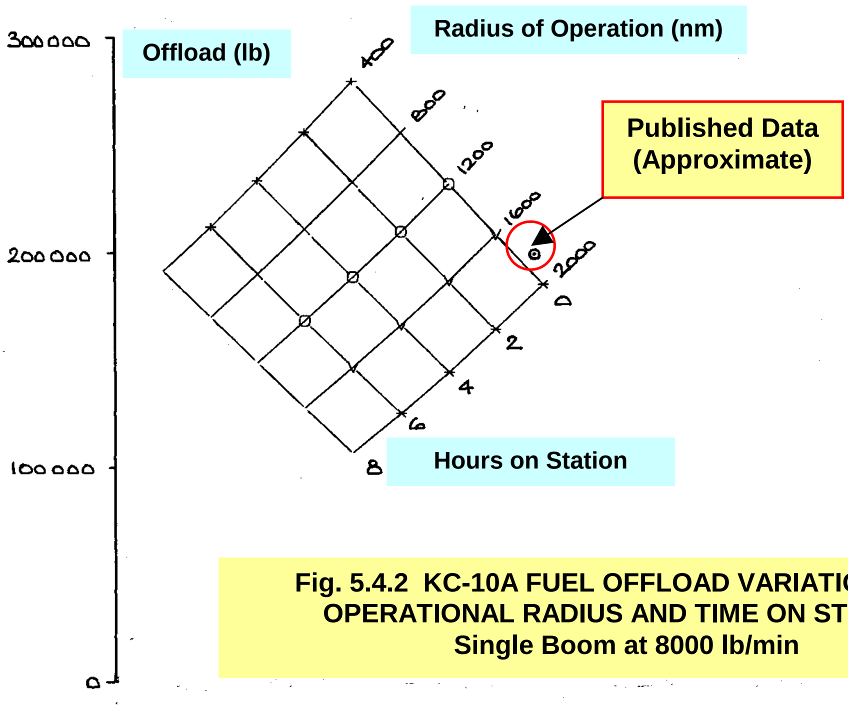


Fig. 5.4.2 KC-10A FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS AND TIME ON STATION
Single Boom at 8000 lb/min

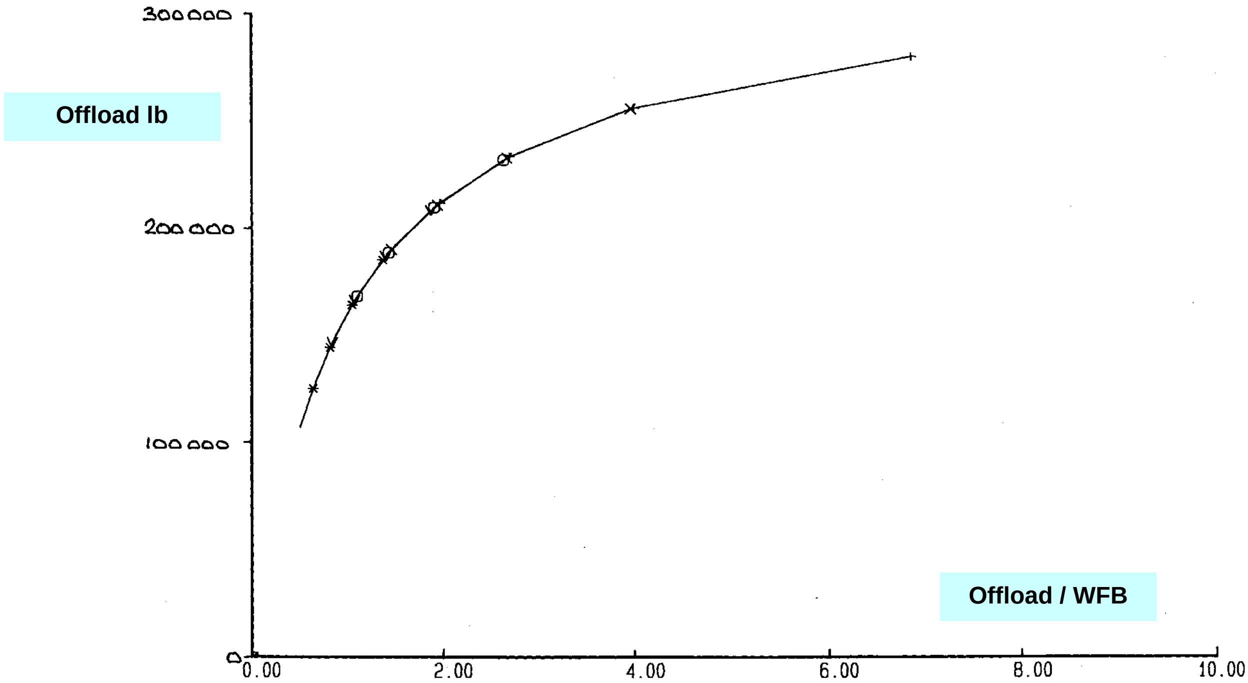


Fig. 5.4.3 KC-10A FUEL OFFLOAD VARIATION WITH FUEL BURN EFFICIENCY
Single Boom at 8000 lb/min

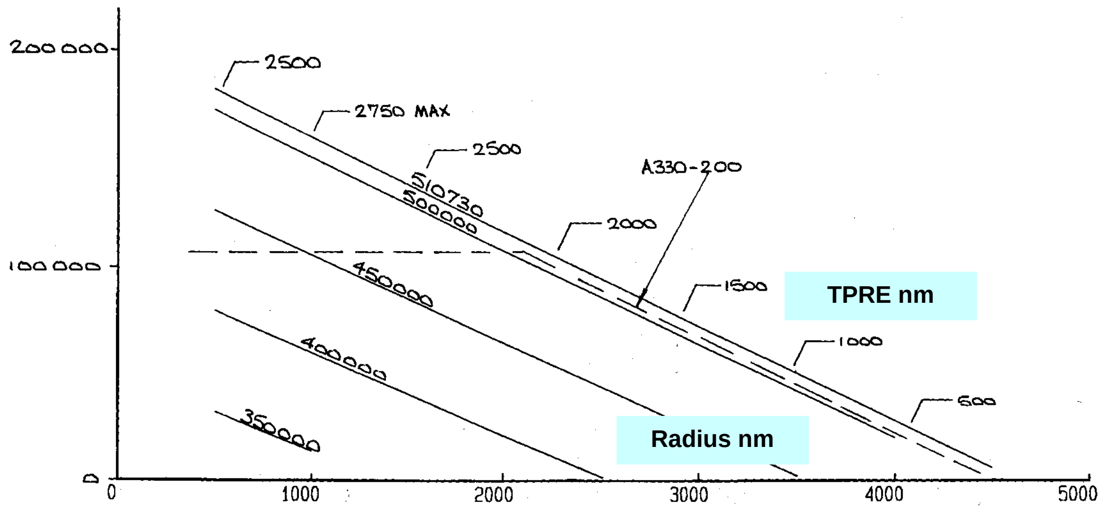


Fig. 5.5.1 A330 MRTT FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS
Two hose and Drogue units at 2800 lb/min each

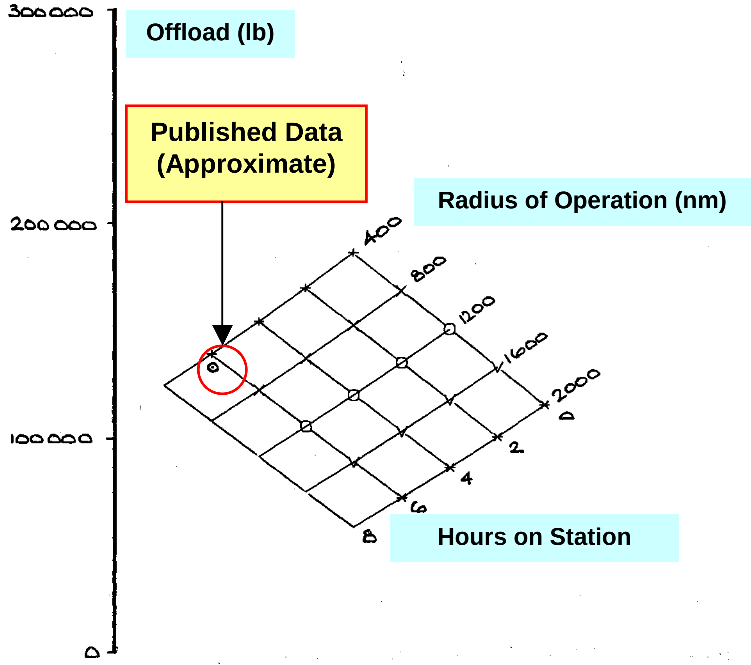


Fig. 5.5.2 A330 MRTT FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS AND TIME ON STATION
Two Hose and Drogue at 2800 lb/min each

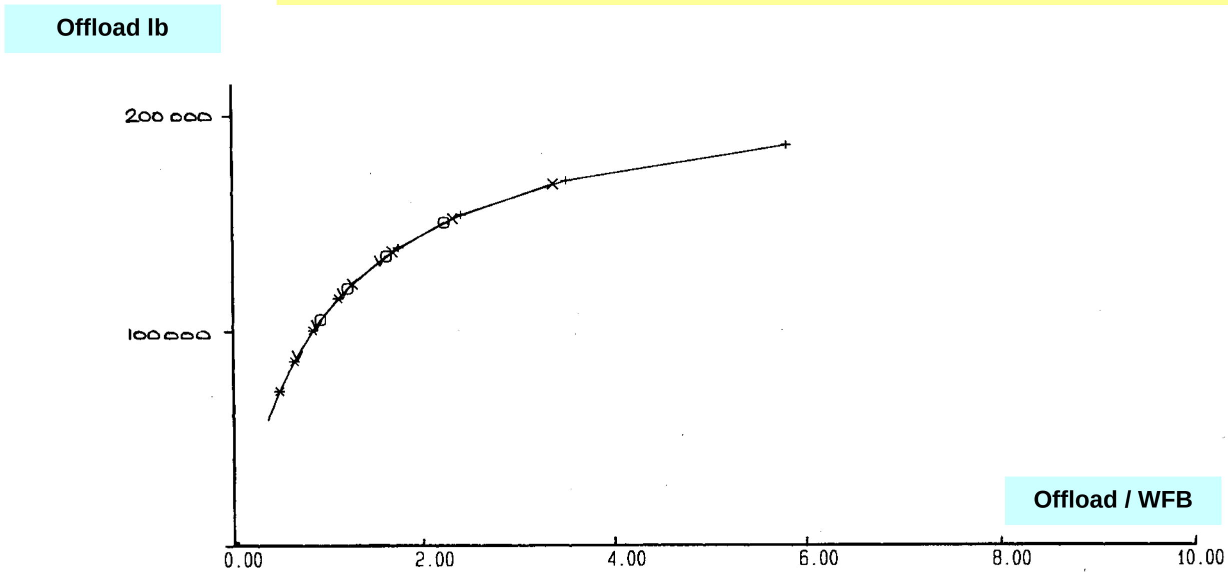


Fig. 5.5.3 A330 MRTT FUEL OFFLOAD VARIATION WITH FUEL BURN EFFICIENCY
Two Hose and Drogue at 2800 lb/min each

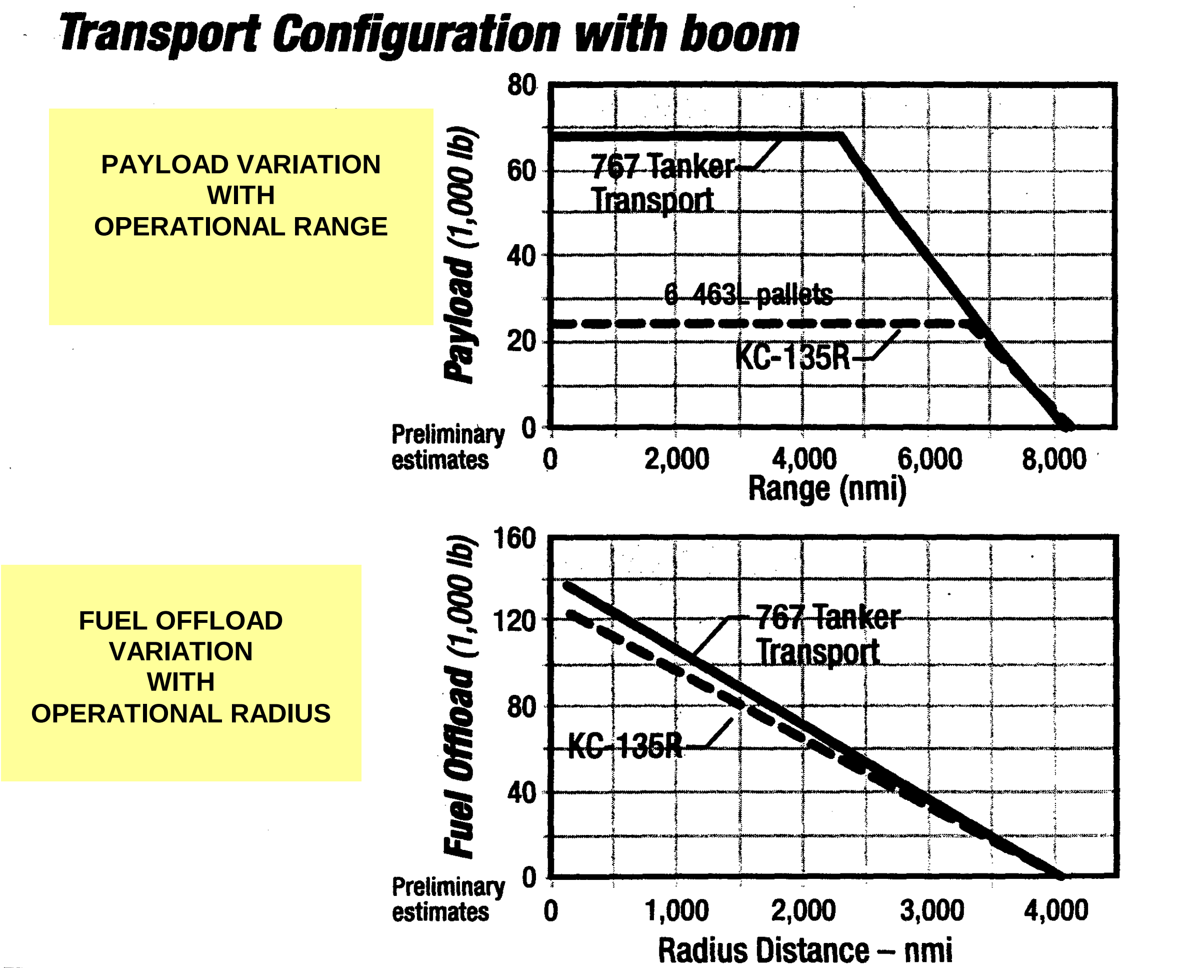


Fig. 5.6.1 KC-767 MANUFACTURER PRELIMINARY PERFORMANCE DATA

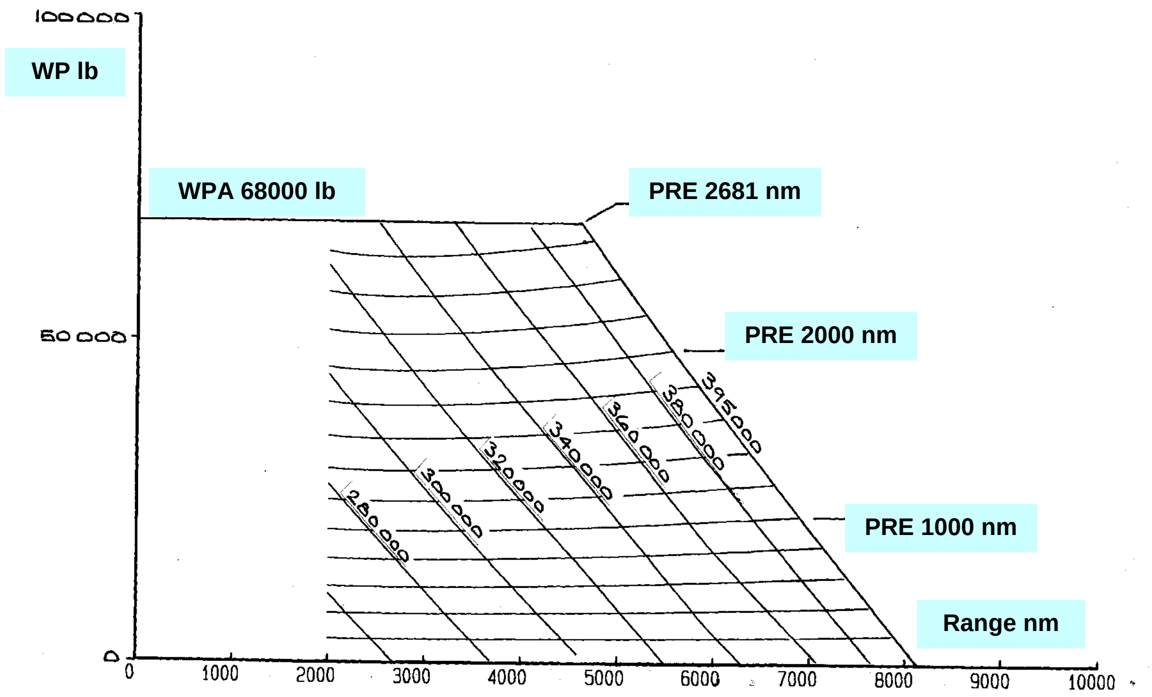


Fig. 5.6.2 KC-767 PAYLOAD v RANGE DIAGRAM, ISO PRE LINES, ISO TOW LINES

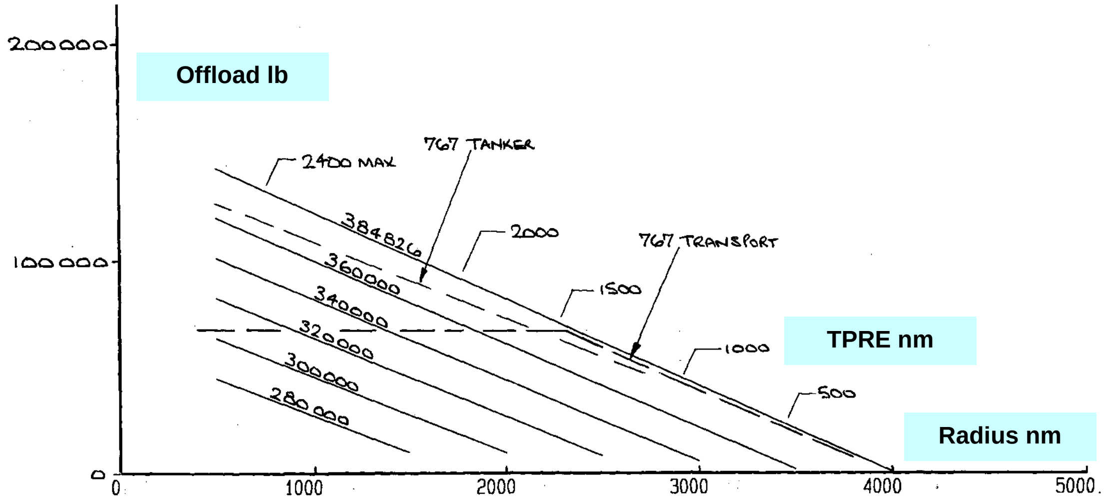


Fig. 5.6.3 KC-767 FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS
Boom at 8000 lb/min

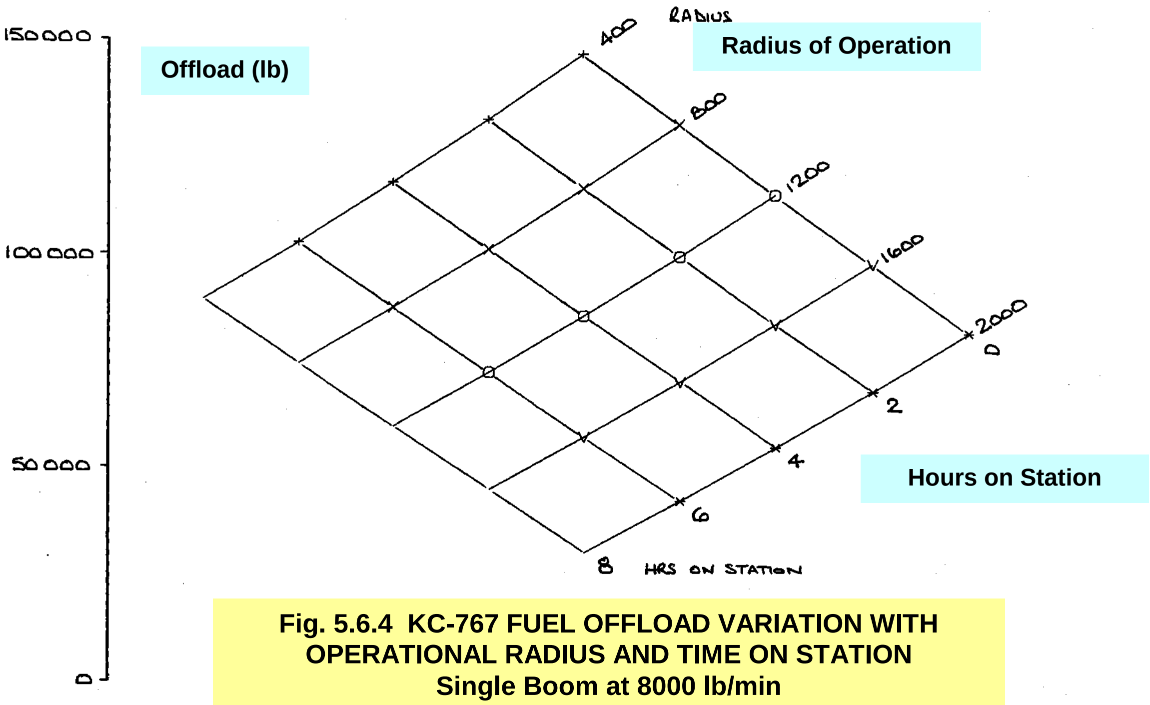


Fig. 5.6.4 KC-767 FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS AND TIME ON STATION
Single Boom at 8000 lb/min

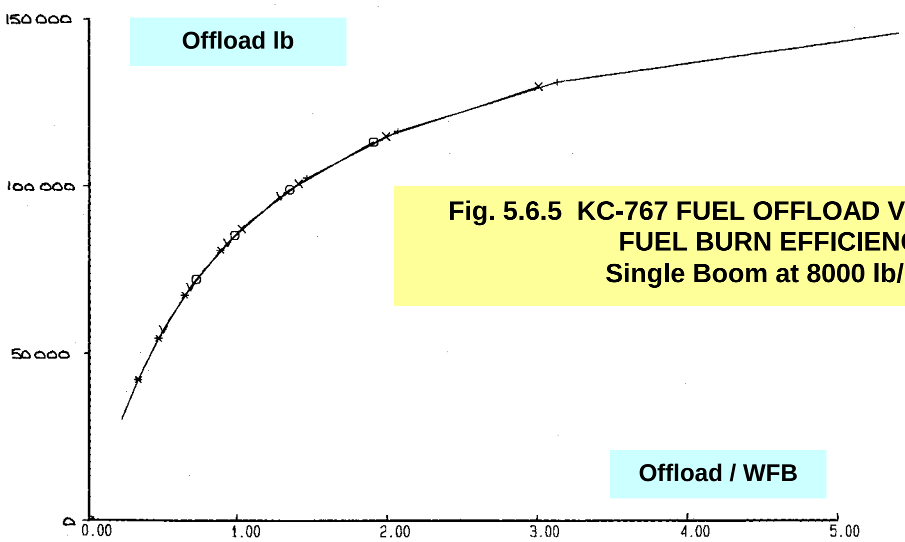


Fig. 5.6.5 KC-767 FUEL OFFLOAD VARIATION WITH FUEL BURN EFFICIENCY
Single Boom at 8000 lb/min

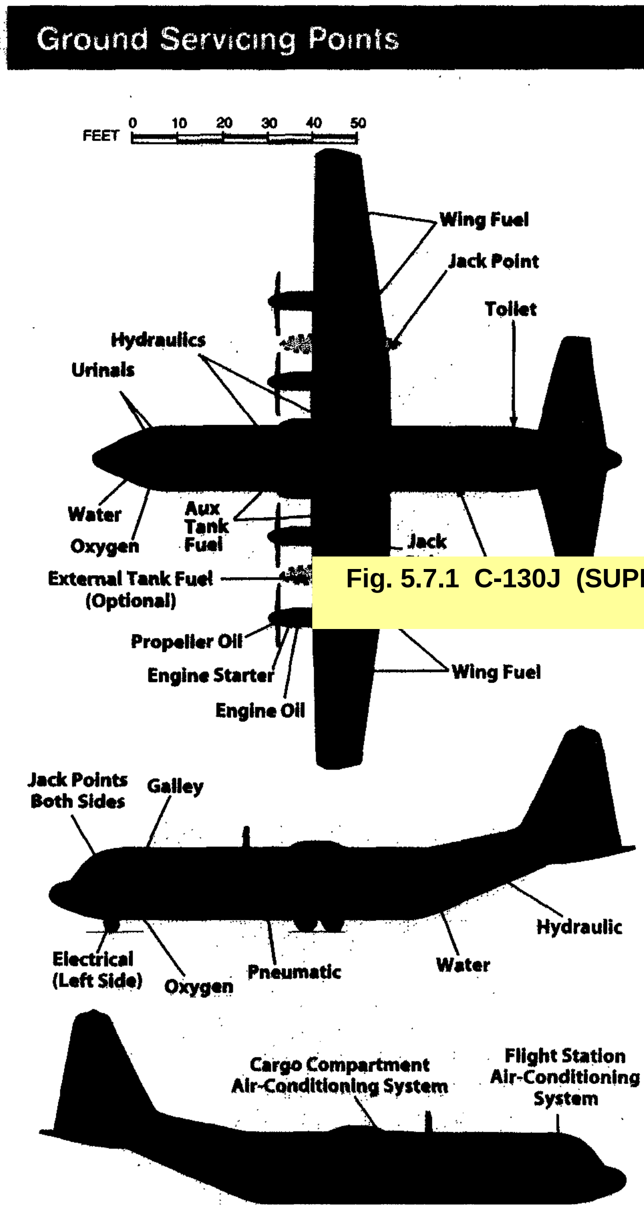


Fig. 5.7.1 C-130J (SUPER HERCULES) GENERAL ARRANGEMENT

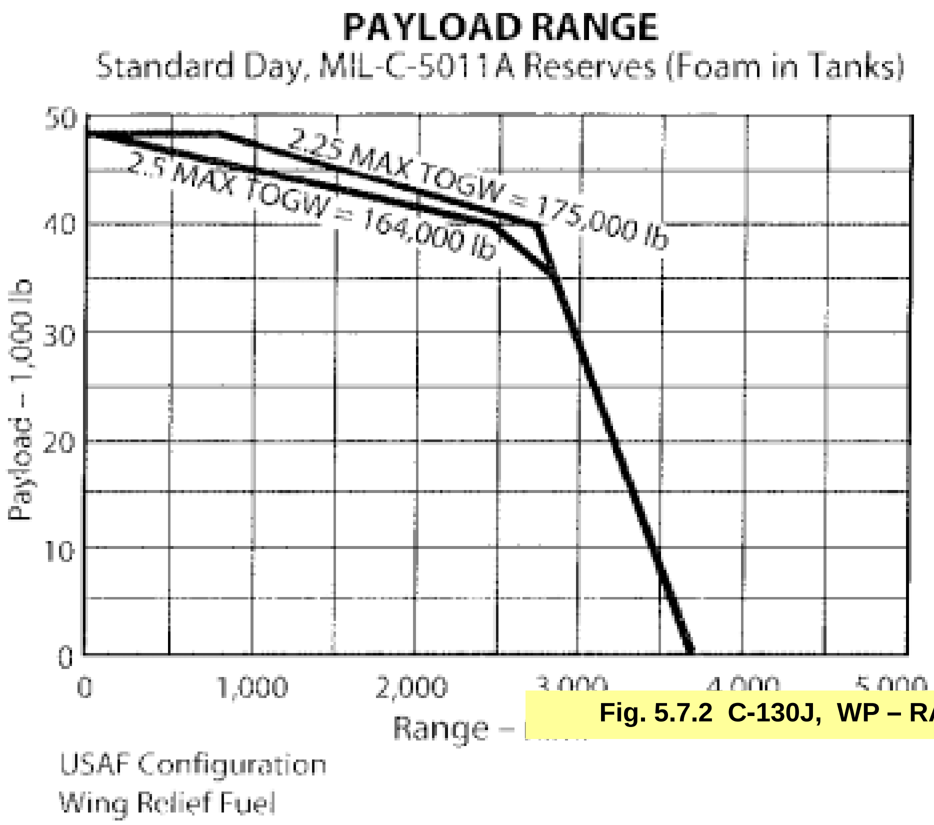
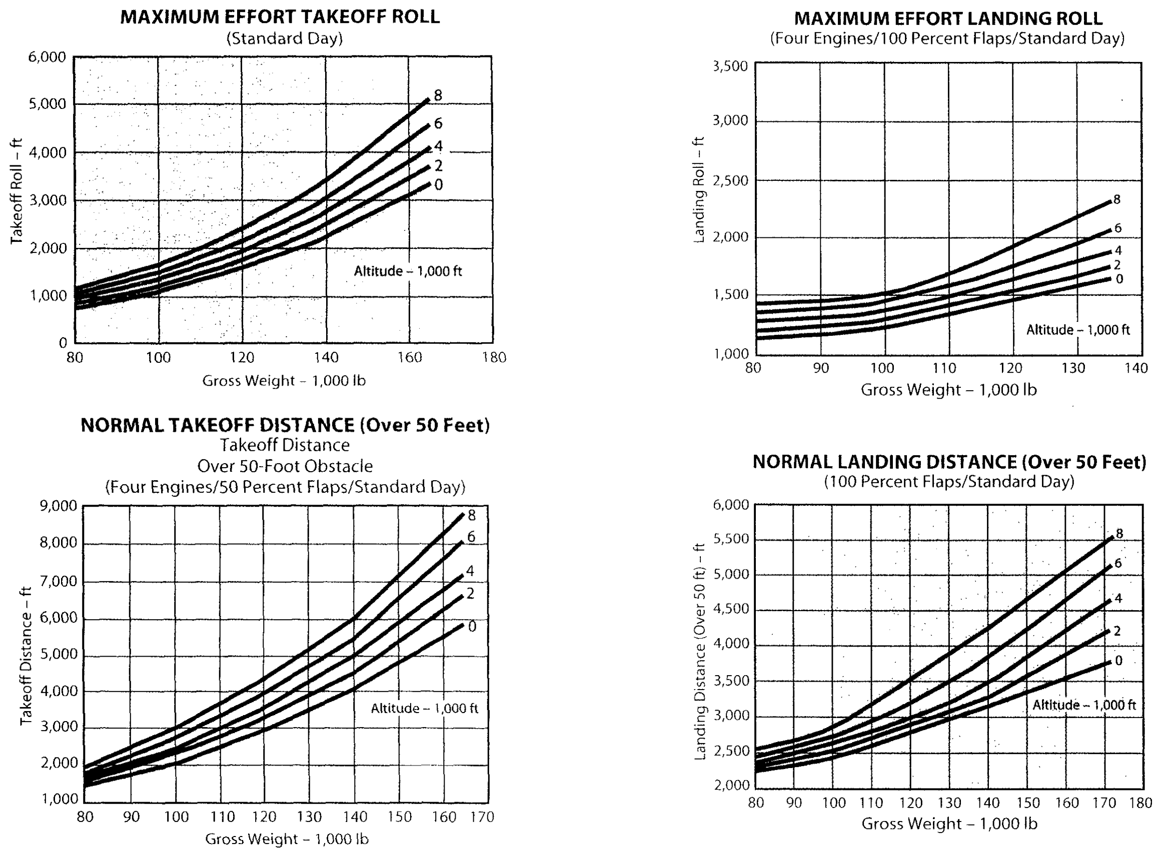


Fig. 5.7.2 C-130J, WP – RANGE



(a) TAKE-OFF **(b) LANDING**

Fig. 5.7.3 C-130J, FIELD PERFORMANCE CAPABILITY

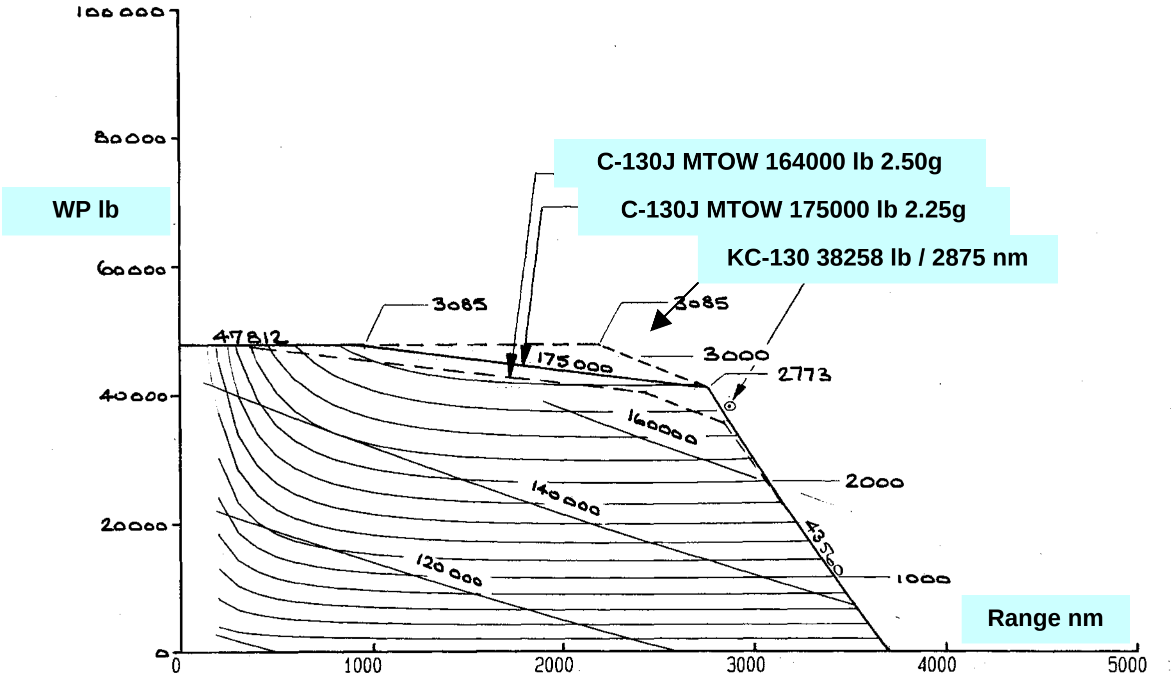


Fig. 5.7.4 C-130J, PAYLOAD – RANGE DIAGRAM, 2.25 and 2.50 g OPERATION ISO PRE LINES, ISO TOW LINES, TYPICAL KC-130J OPERATING POINT FOR COMPARISON

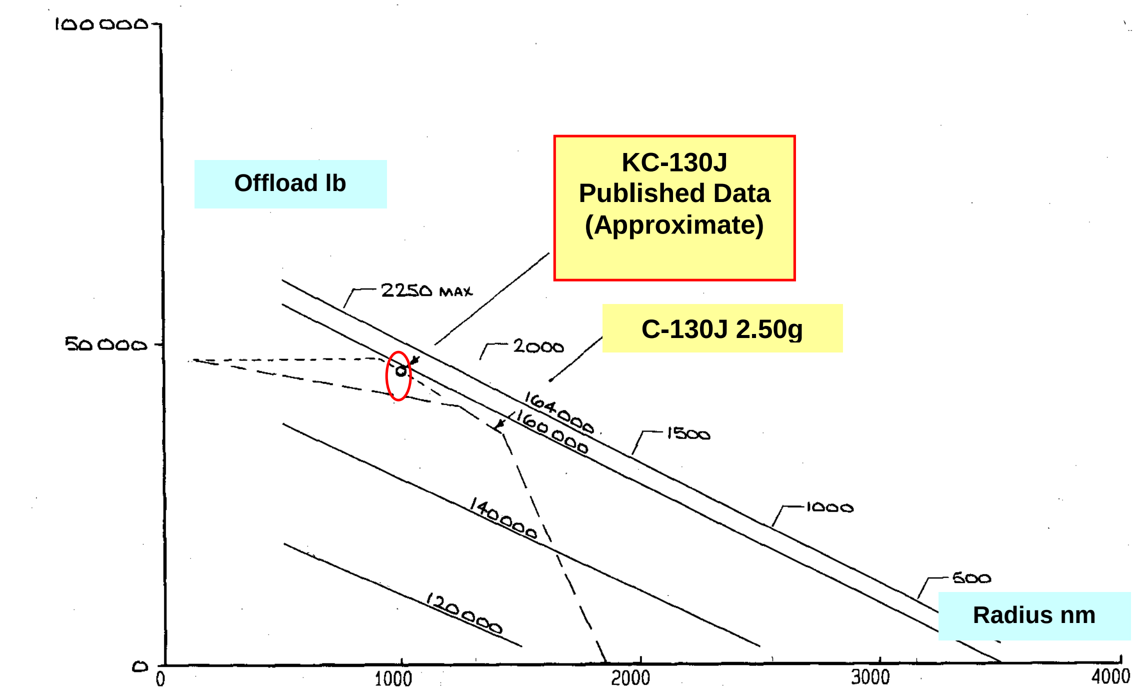


Fig. 5.7.5 KC-130J FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS Two Hose and Drogue at 2000 lb/min each

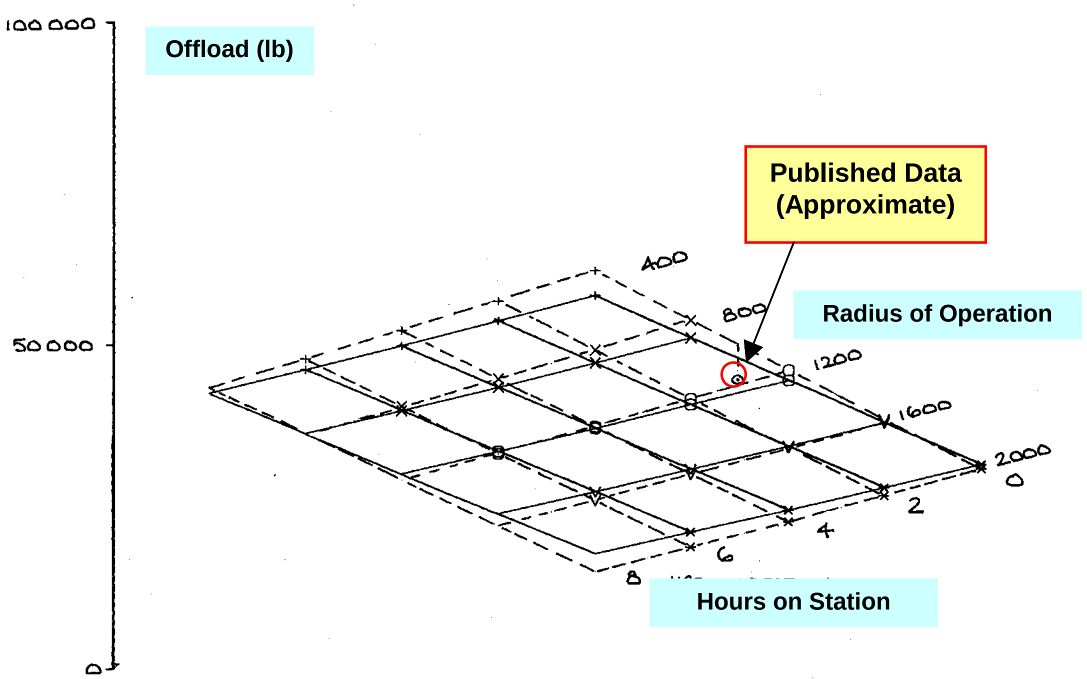
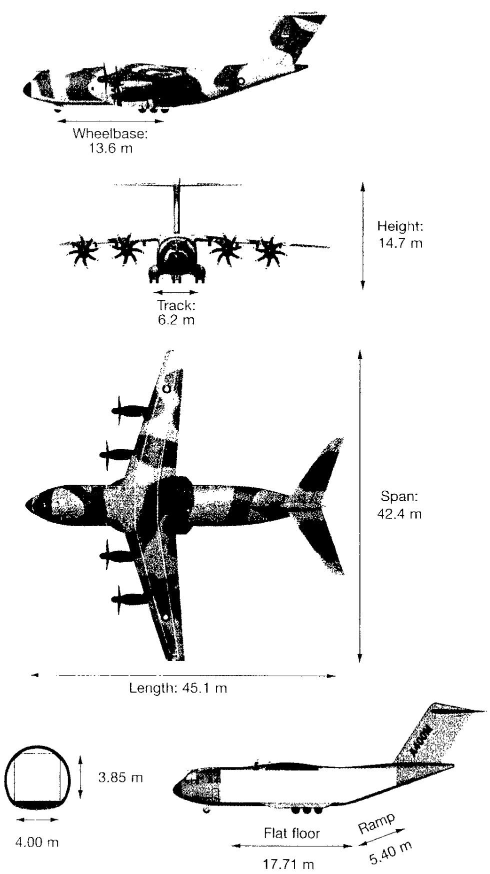
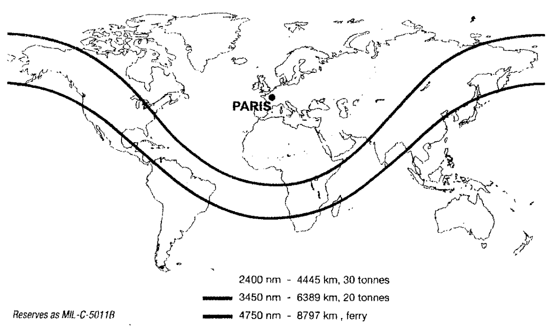


Fig. 5.7.6 KC-130J FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS AND TIME ON STATION, Two Hose and Drogue at 2000 lb/min each, 7% MTOW Reserves (solid) & 4% MTOW Reserves (dashed)



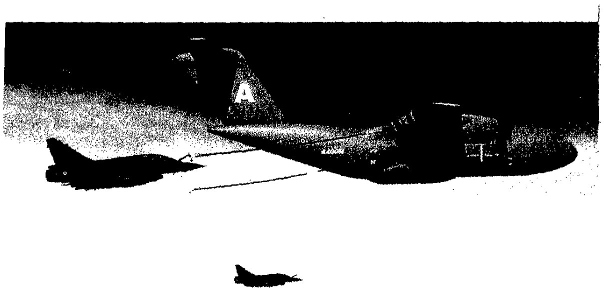
Max. Logistic T.O. Weight	(2.25 g)	136 500 kg	(300 931 lb)
Max. Tactical T.O. Weight	(2.5 g)	127 500 kg	(281 089 lb)
Max. Logistic LDG Weight	(2.25 g)	120 000 kg	(264 554 lb)
Max. Tactical LDG Weight	(2.5 g)	113 000 kg	(249 122 lb)
Max. Logistic Payload	(2.25 g)	37 000 kg	(81 571 lb)
Max. Tactical Payload	(2.5 g)	30 000 kg	(66 139 lb)
Internal Fuel Weight		47 700 kg	(105 160 lb)
Operating Weight Empty		76 500 kg	(168 653 lb)
Total Cargo Floor Area	(incl. ramp)	92 m²	(990 ft²)
Gross Cargo Hold Volume	(incl. ramp)	340 m³	(12 007 ft³)
Flight Crew		2 (+1 Loadmaster)	
Engine		4 x TP400-D6 (EuroProp Int'l) 10 000 shp class each	
Propeller		4 x FH386 (Ratier-Figeac) 8 composite blades	
Max. Operating Altitude – Normal Ops		11 278 m	(37 000 ft)
Max. Operating Altitude – Special Ops		12 192 m	(40 000 ft)
Max. Cruise Speed (CAS)		555 km/h	(300 kt)
Max. Cruise Speed (TAS)		780 km/h	(422 kt)
Cruise Speed Range (Mach)		0.68 – 0.72 Mach	



Range capability from Paris

Fig. 5.8.1 AIRBUS A400M, GENERAL ARRANGEMENT, PAYLOAD – RANGE DATA

The flight envelope of the A400M allows it to refuel a wide range of aircraft and helicopters, at the altitudes appropriate to their missions.



- A two-point trailing drogue system can be installed within two hours by fitting two standard air-to-air refuelling pods to the multi-role attachment points on the wings.
- An optional centre-line pallet-mounted hose and drogue unit can be fitted in the rear cargo bay.
- Optional roll-on/roll-off cargo bay tanks can also be installed, providing up to 12 tonnes of extra fuel capacity (provisions as optional).

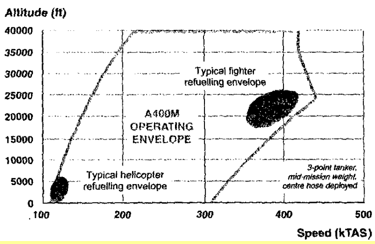
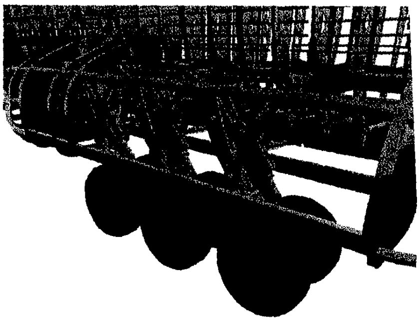


Fig. 5.8.2 A400M, TANKER CAPABILITY, OPERATING ENVELOPE

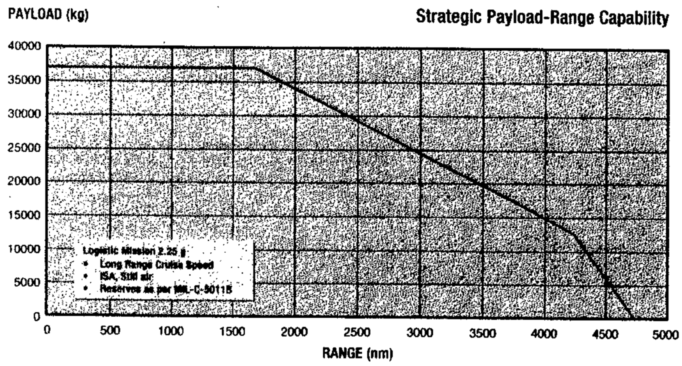
The tandem multi-wheel main landing gear provides excellent soft field capabilities, thus allowing the A400M to operate from austere, semi-prepared runways.

Three independent lever type struts per landing gear provide good response over bumps in rugged terrain and evenly distribute ground loads into the fuselage structure.

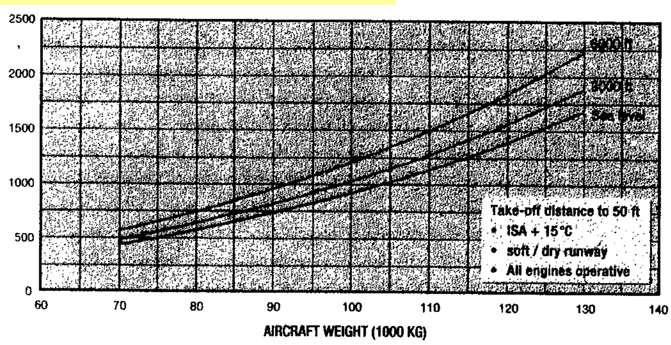


Hydraulic chambers (in addition to the shock absorbers) are included as part of the main landing gear and are filled as appropriate to raise and lower the rear fuselage to ease cargo loading/unloading operations.

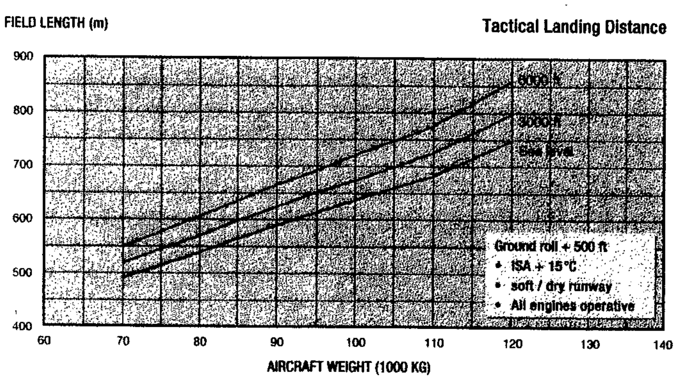
(a) SOFT FIELD CAPABILITY



(b) PAYLOAD - RANGE



(c) TACTICAL TAKE-OFF, DISTANCE (ft) – AIRCRAFT WEIGHT, ISA + 15°C, ALL ENGINES



(d) TACTICAL LANDING, DISTANCE (ft) – AIRCRAFT WEIGHT, ISA + 15°C, ALL ENGINES

Fig. 5.8.3 A400M, PAYLOAD – RANGE & FIELD PERFORMANCE, 2.25g LIMITATIONS, Fuel Reserves – MIL-C-5011B

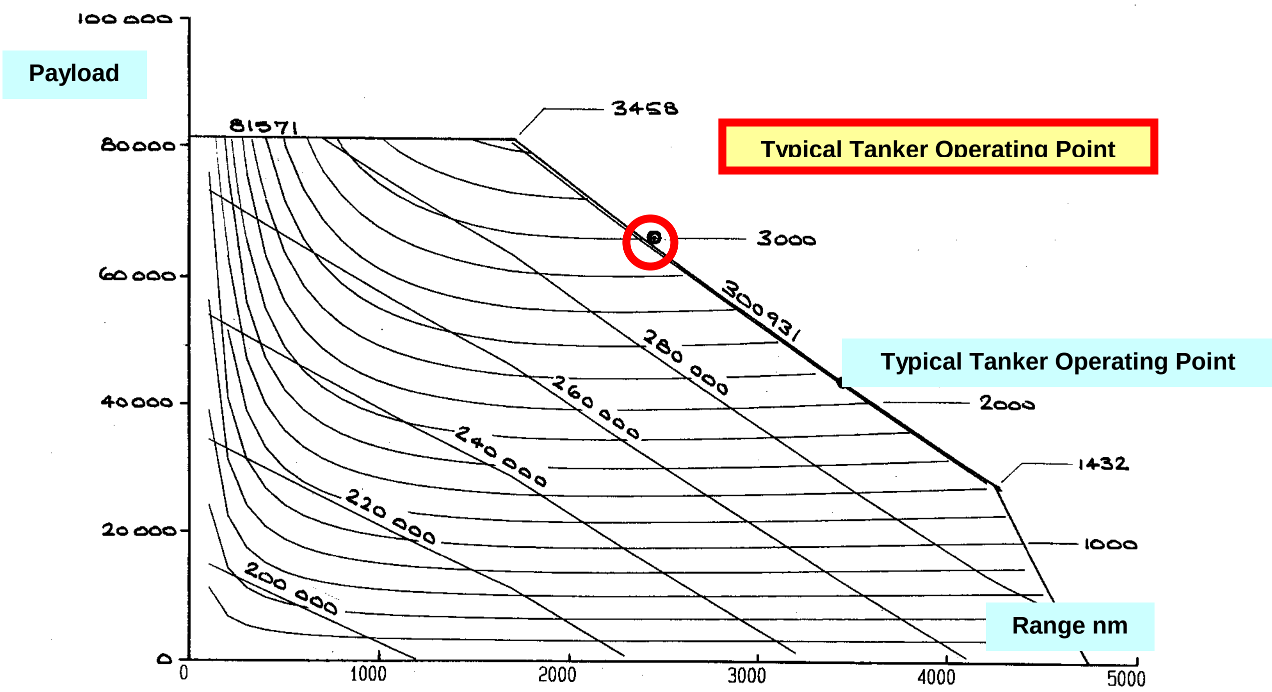


Fig. 5.8.4 A400M, PAYLOAD – RANGE DIAGRAM, 2.25 g OPERATION
ISO PRE LINES, ISO TOW LINES,
TYPICAL A400M TANKER OPERATING POINTS FOR COMPARISON

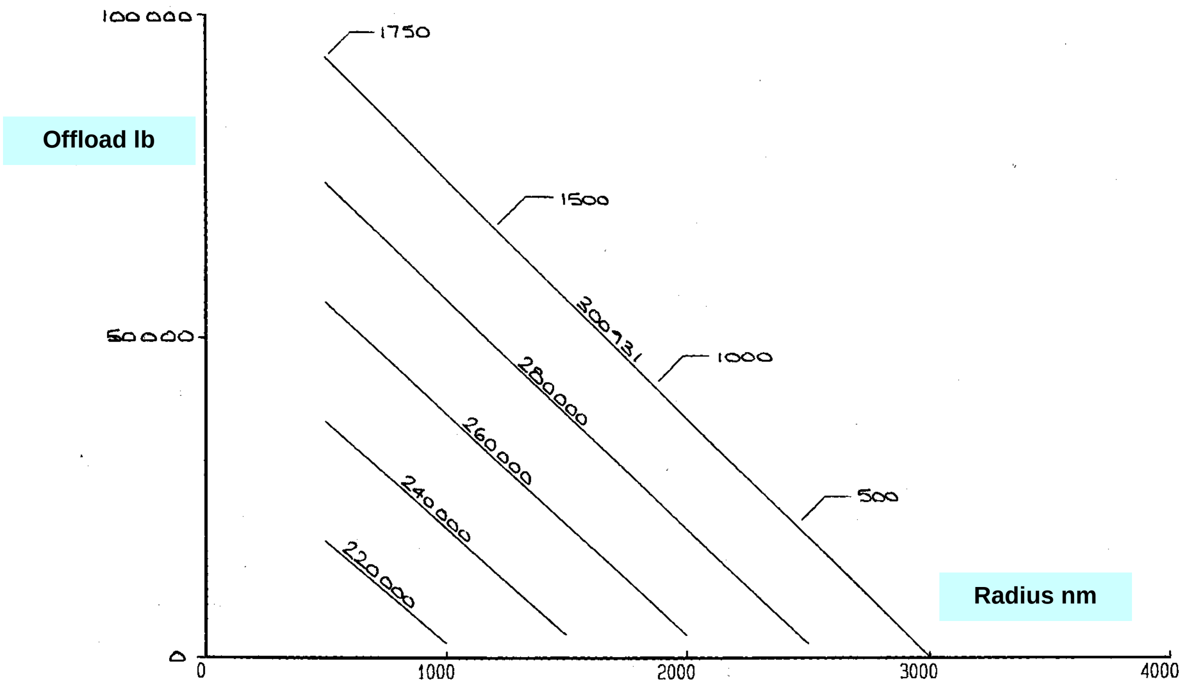


Fig. 5.8.5 A400M FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS
Two Hose and Drogue at 2650 lb/min each

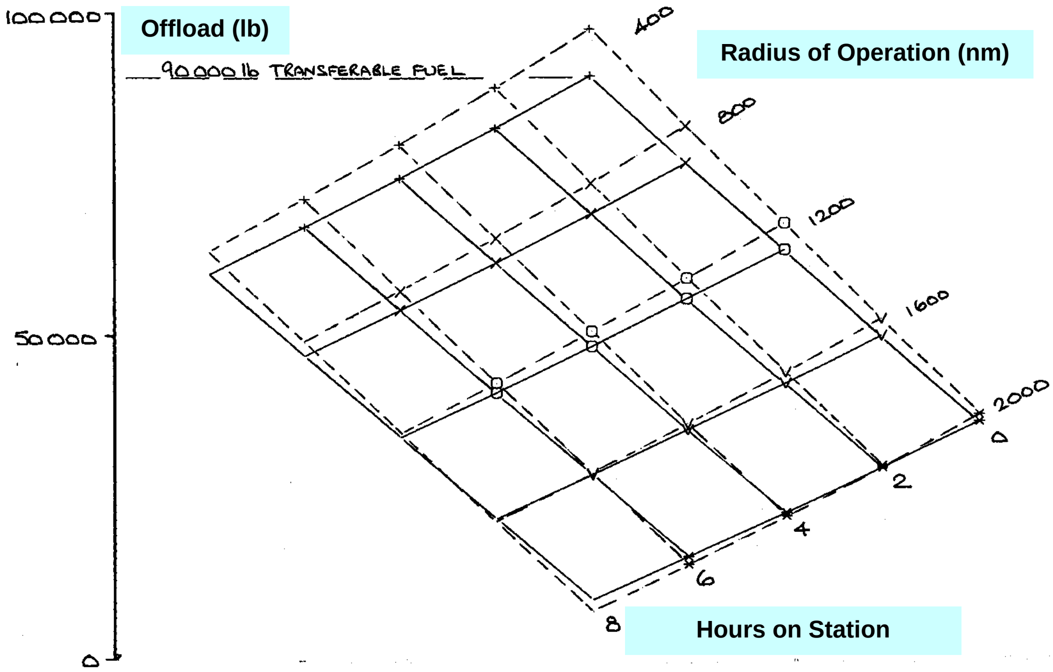


Fig. 5.8.6 A400M FUEL OFFLOAD VARIATION WITH OPERATIONAL RADIUS AND TIME ON STATION, Two Hose and Drogue at 2650 lb/min each, 7% MTOW Reserves (solid) & 4% MTOW Reserves (dashed)

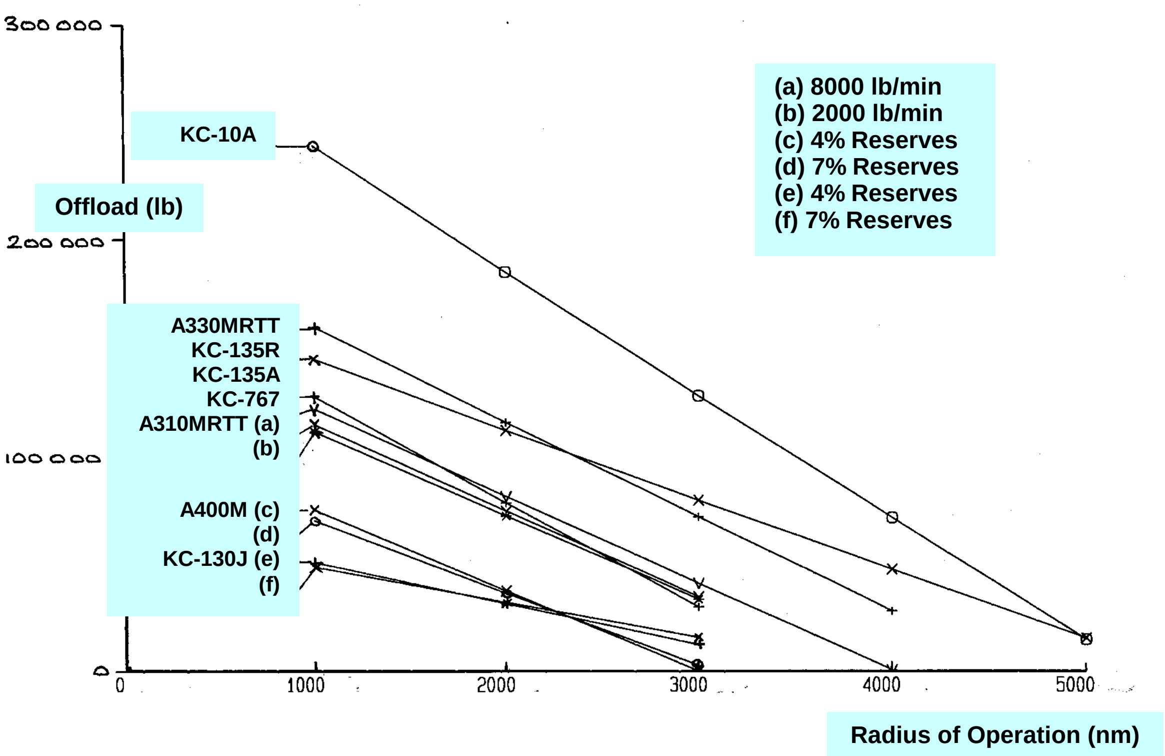


Fig. 5.9.1 OFFLOAD (lb) VARIATION WITH RADIUS OF OPERATION (nm) JET and TURBO-PROP TANKERS, EFFECT OF TRANSFER RATE

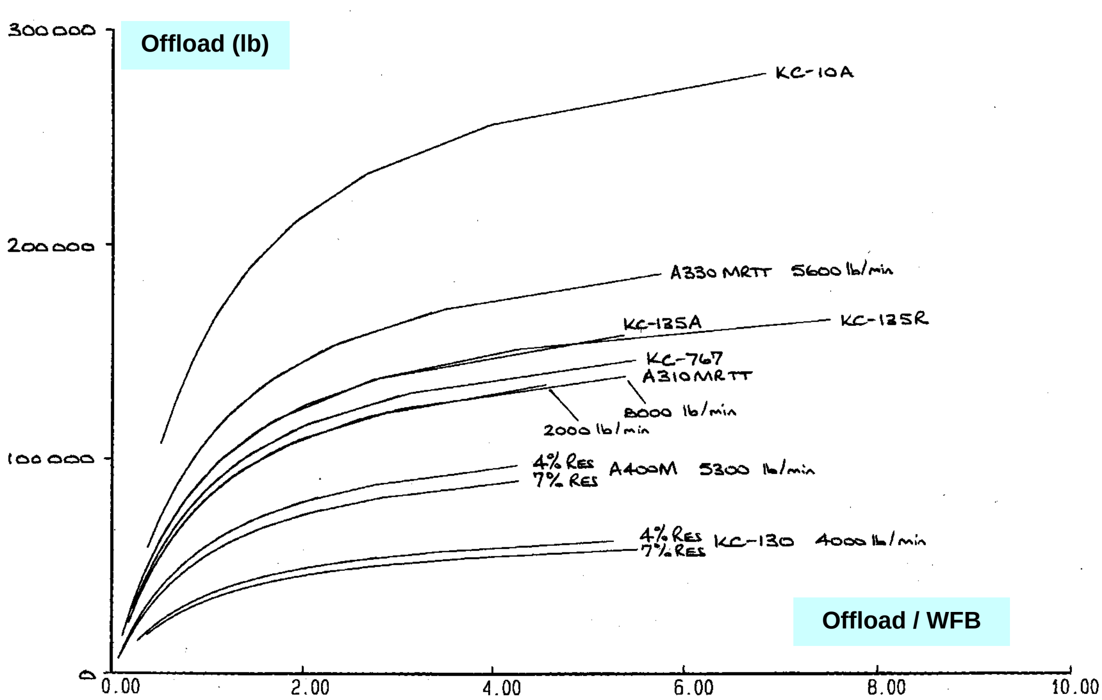


Fig. 5.9.2 OFFLOAD VARIATION WITH OFFLOAD / TOTAL TANKER FUEL CONSUMED, JET and TURBO-PROP TANKERS COMPARED, EFFECT OF TRANSFER RATE

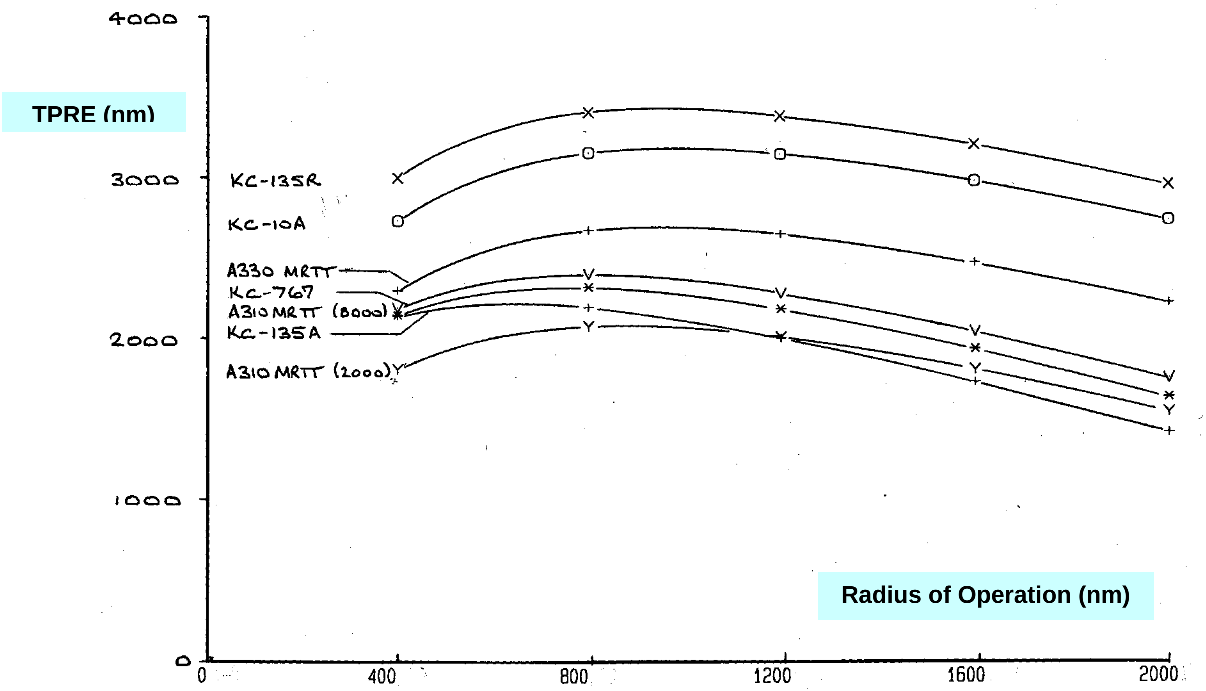


Fig. 5.9.3 TANKER PAYLOAD RANGE EFFICIENCY (TPRE) VARIATION WITH RADIUS OF OPERATION, JET TANKERS, ZERO HOURS ON STATION

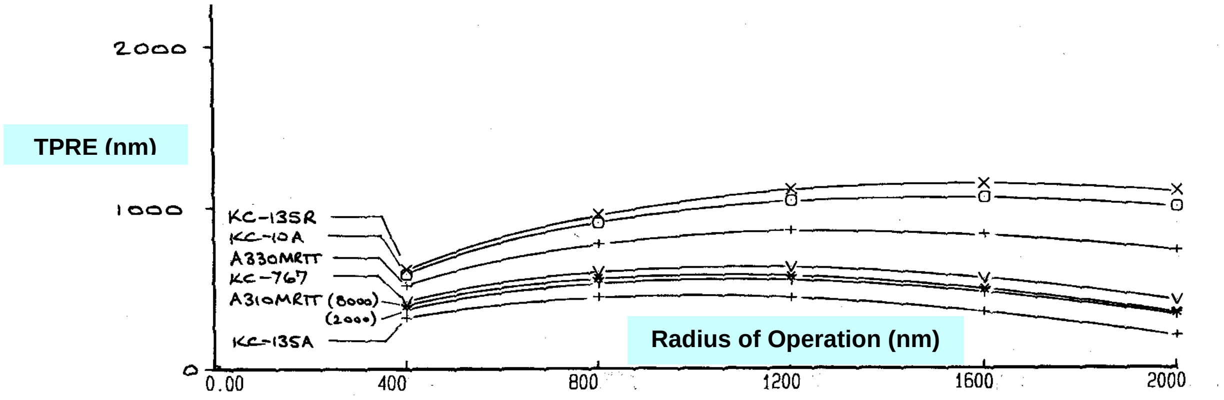


Fig. 5.9.4 TANKER PAYLOAD RANGE EFFICIENCY (TPRE) VARIATION WITH RADIUS OF OPERATION, JET TANKERS, EIGHT HOURS ON STATION

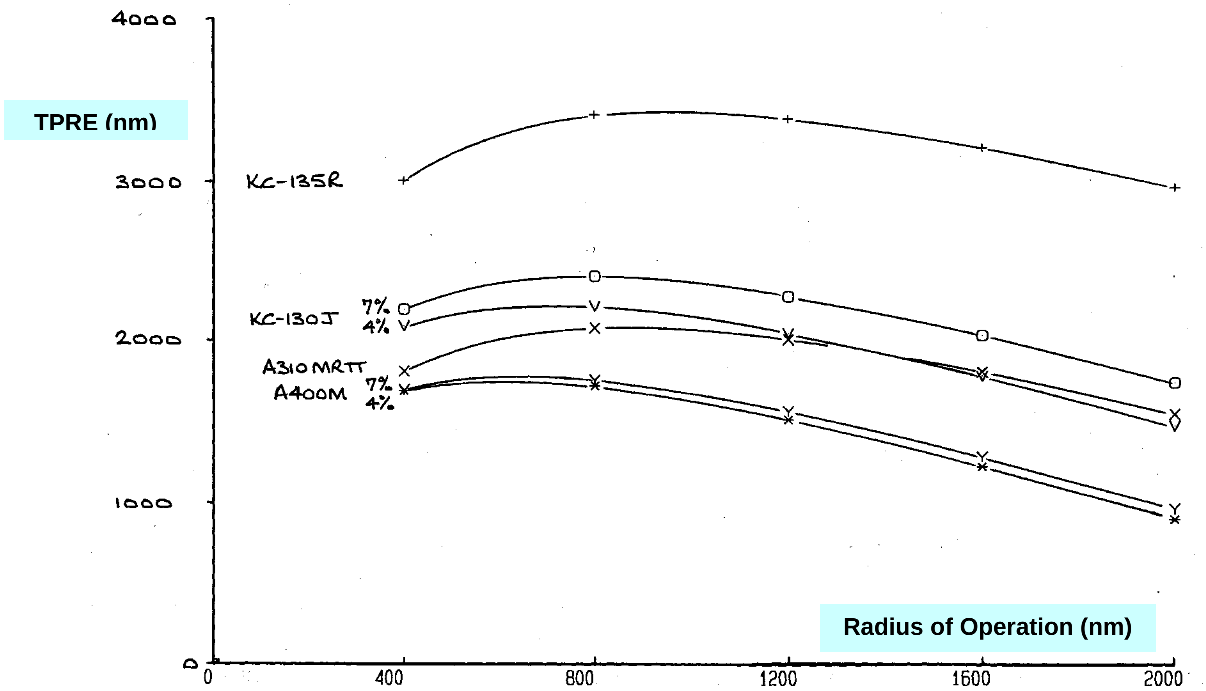


Fig. 5.9.5 TANKER PAYLOAD RANGE EFFICIENCY (TPRE) VARIATION WITH RADIUS OF OPERATION, TURBO-PROP TANKERS, ZERO HOURS ON STATION

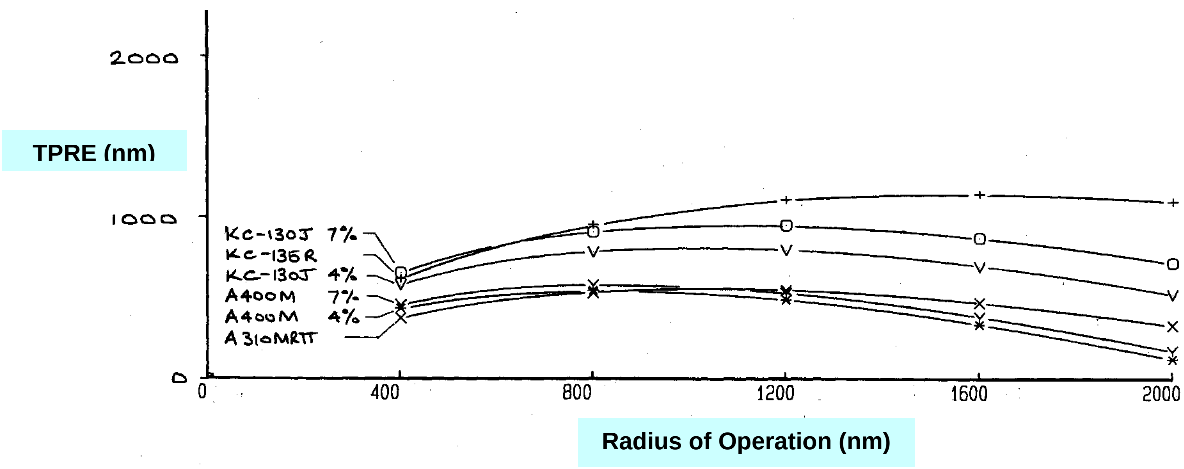


Fig. 5.9.6 TANKER PAYLOAD RANGE EFFICIENCY (TPRE) VARIATION WITH RADIUS OF OPERATION, TURBO-PROP TANKERS, EIGHT HOURS ON STATION

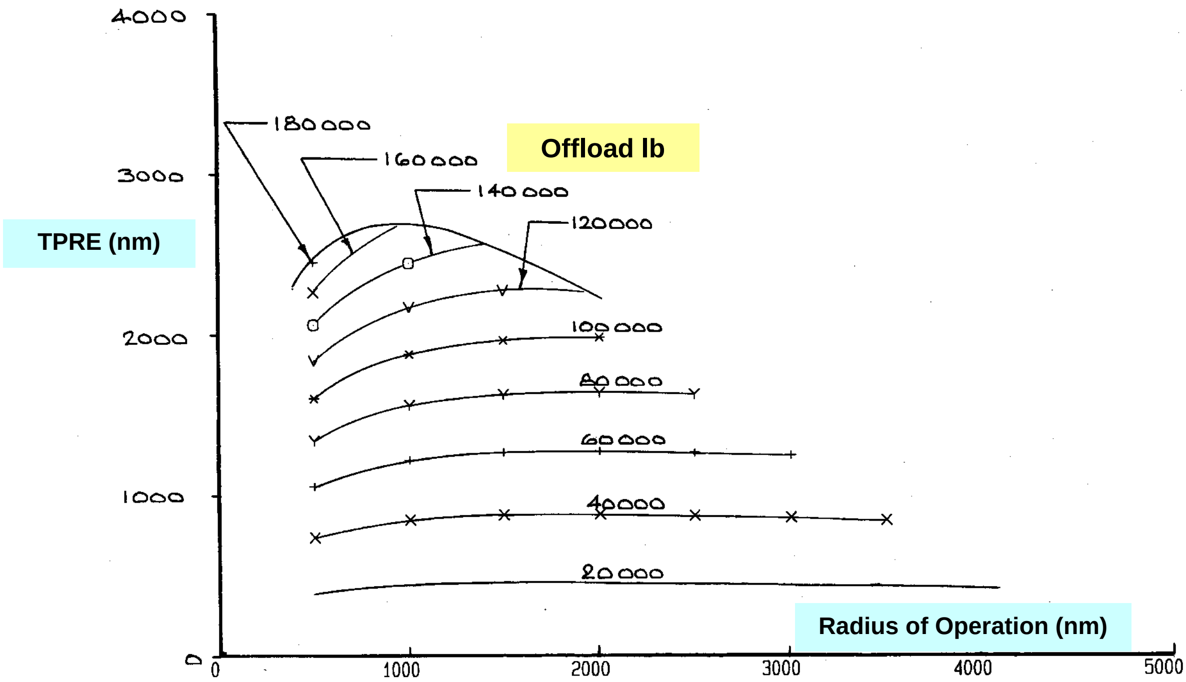


Fig. 5.9.7 A330 MRTT, TPRE v RADIUS OF OPERATION, ZERO HOURS ON STATION EFFECT OF OFFLOAD VARIATION

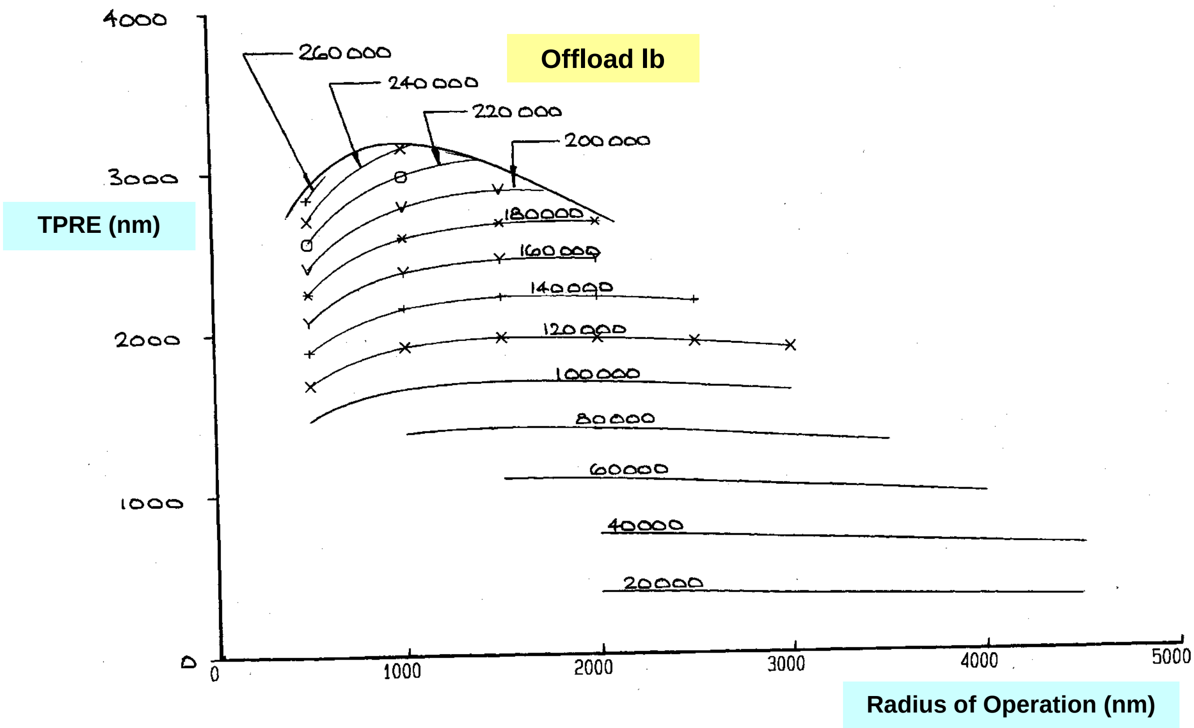


Fig. 5.9.8 KC-10A, TPRE v RADIUS OF OPERATION, ZERO HOURS ON STATION EFFECT OF OFFLOAD VARIATION

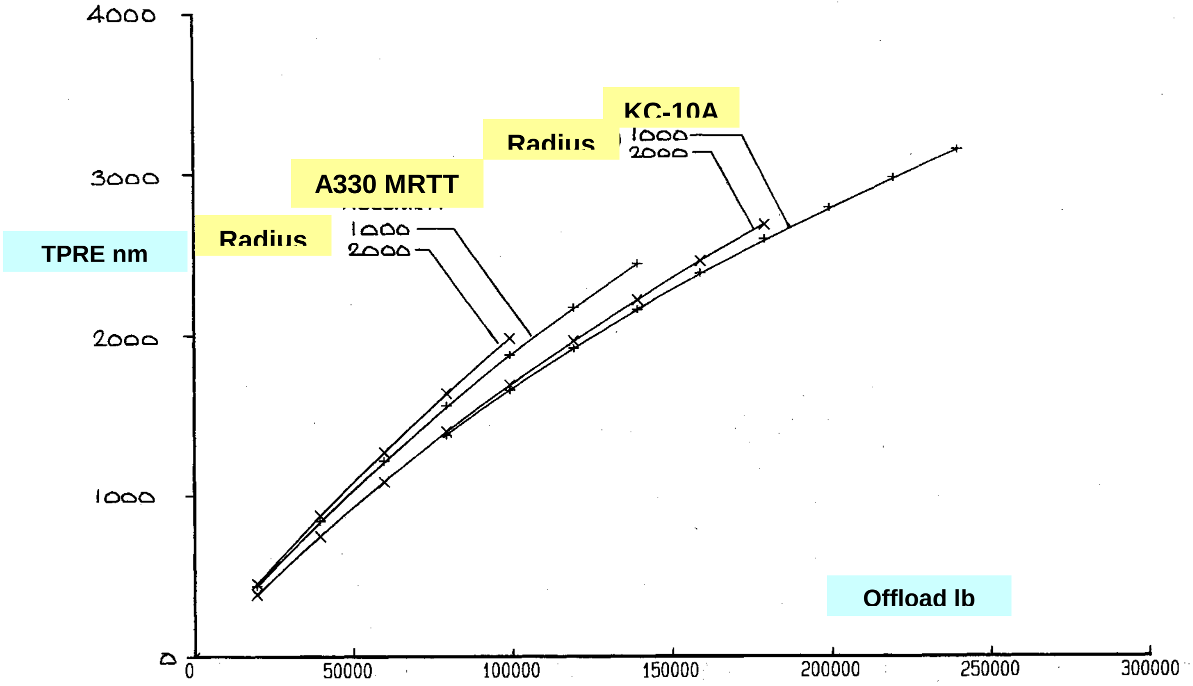


Fig. 5.9.9 A330 MRTT and KC-10A COMPARED, TPRE v OFFLOAD, ZERO HOURS ON STATION EFFECT OF RADIUS OF OPERATION

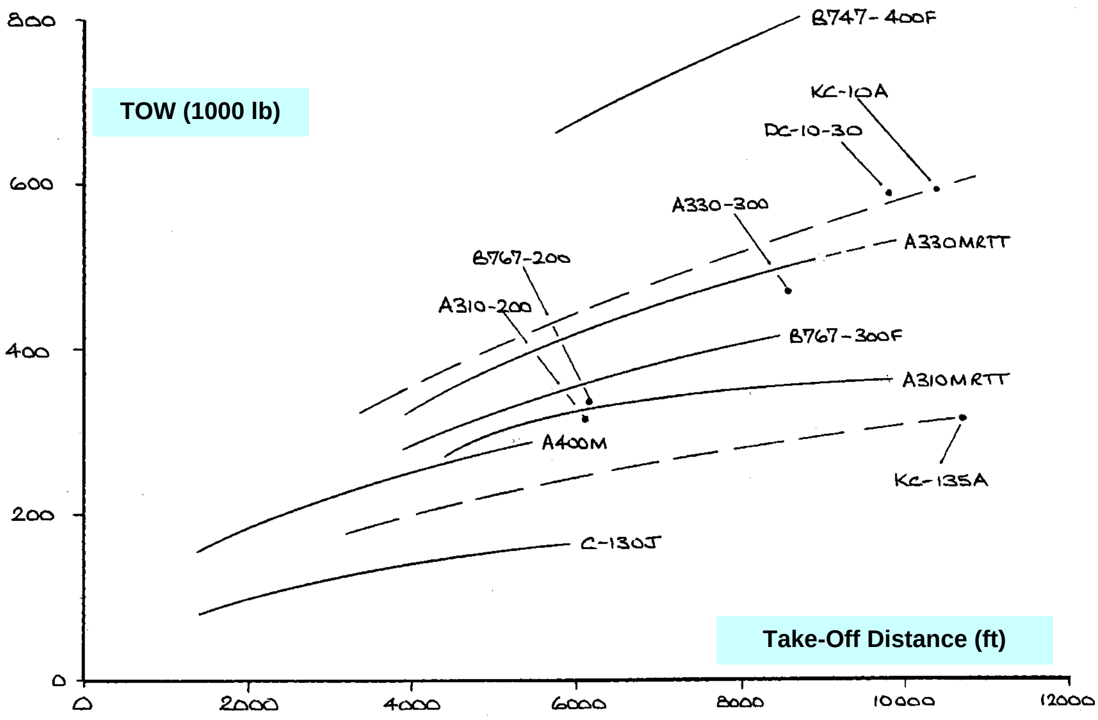


Fig. 5.9.10 TANKER TOW VARIATION WITH TAKE-OFF DISTANCE, JET and TURBO-PROP TANKERS

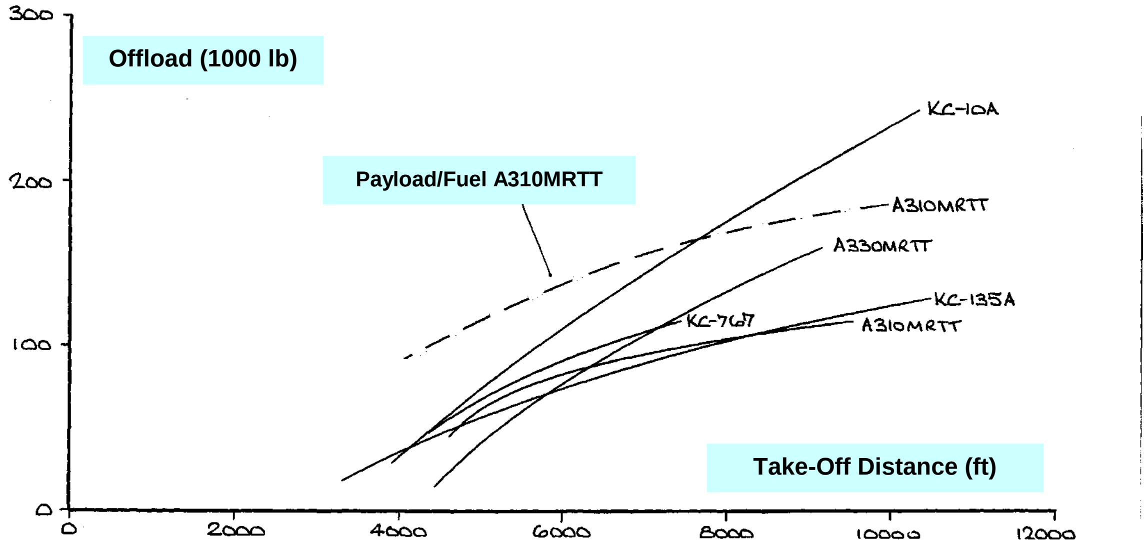


Fig. 5.9.11 TANKER OFFLOAD AT 1000 nm RADIUS VARIATION WITH TAKE-OFF DISTANCE, JET and TURBO-PROP TANKERS

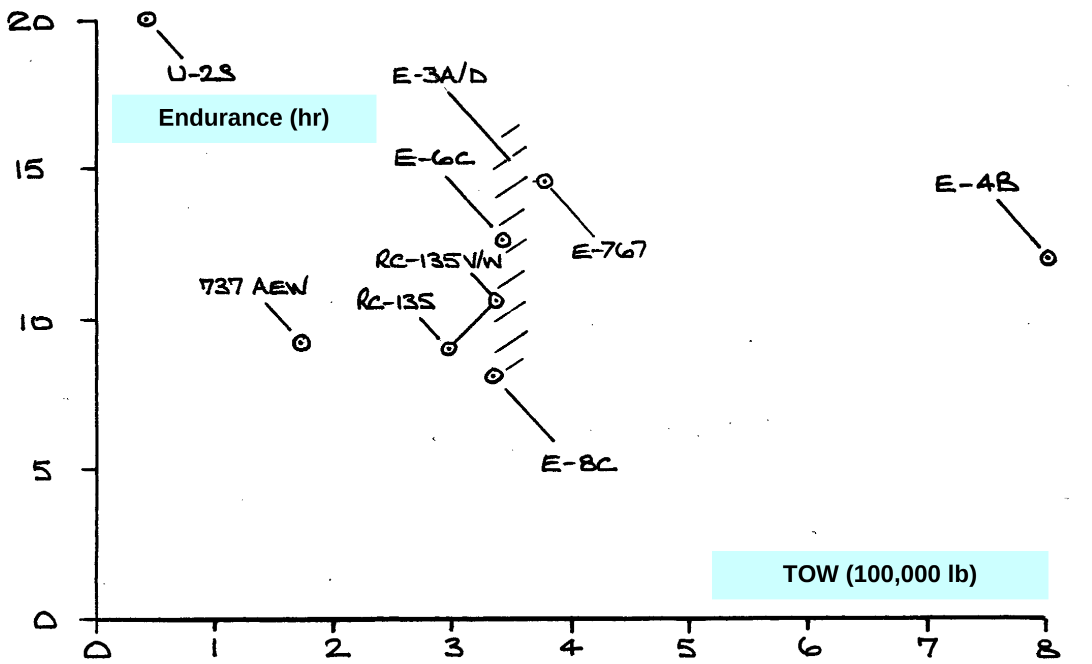


Fig. 6.1.1 ENDURANCE v TOW, MANNED SURVEILLANCE AIRCRAFT

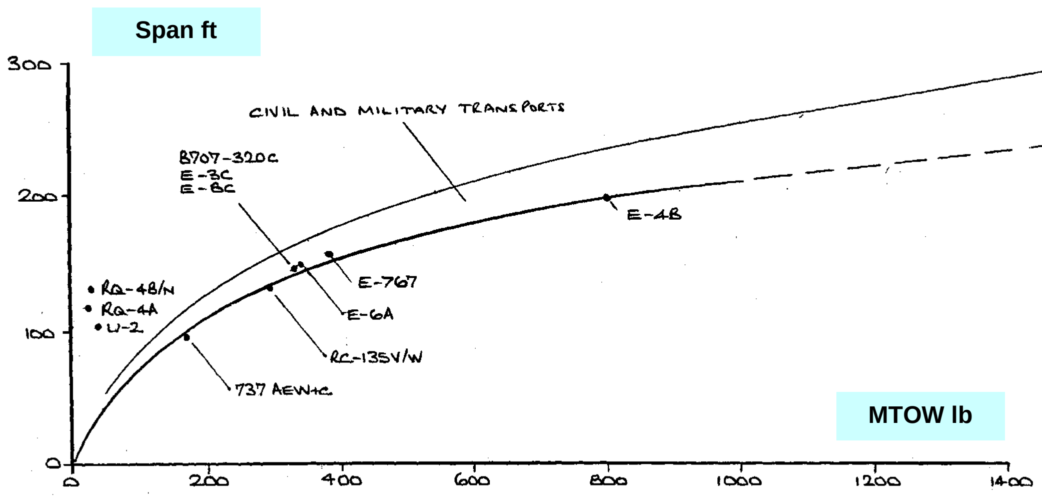


Fig. 6.1.2 SURVEILLANCE AIRCRAFT, SPAN (b ft) - MTOW,
CIVIL and MILITARY TRANSPORT TRENDS

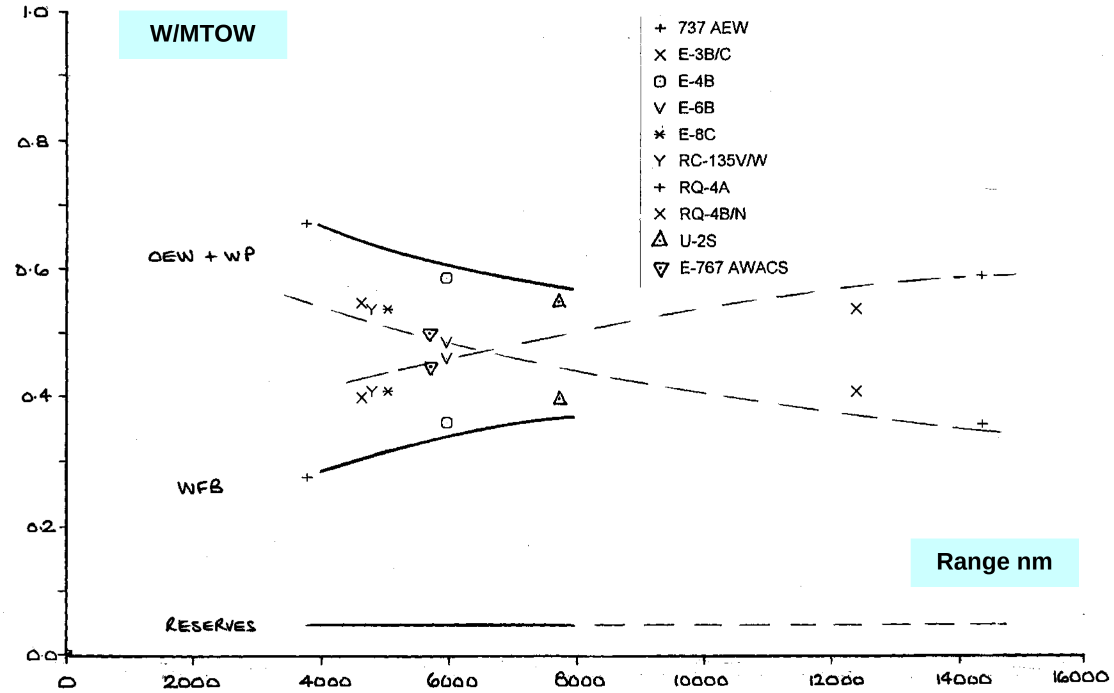


Fig. 6.1.3 SURVEILLANCE AIRCRAFT, WEIGHT RATIOS wrt MTOW v POINT B RANGE,
CIVIL FREIGHTER JET AIRCRAFT TRENDS

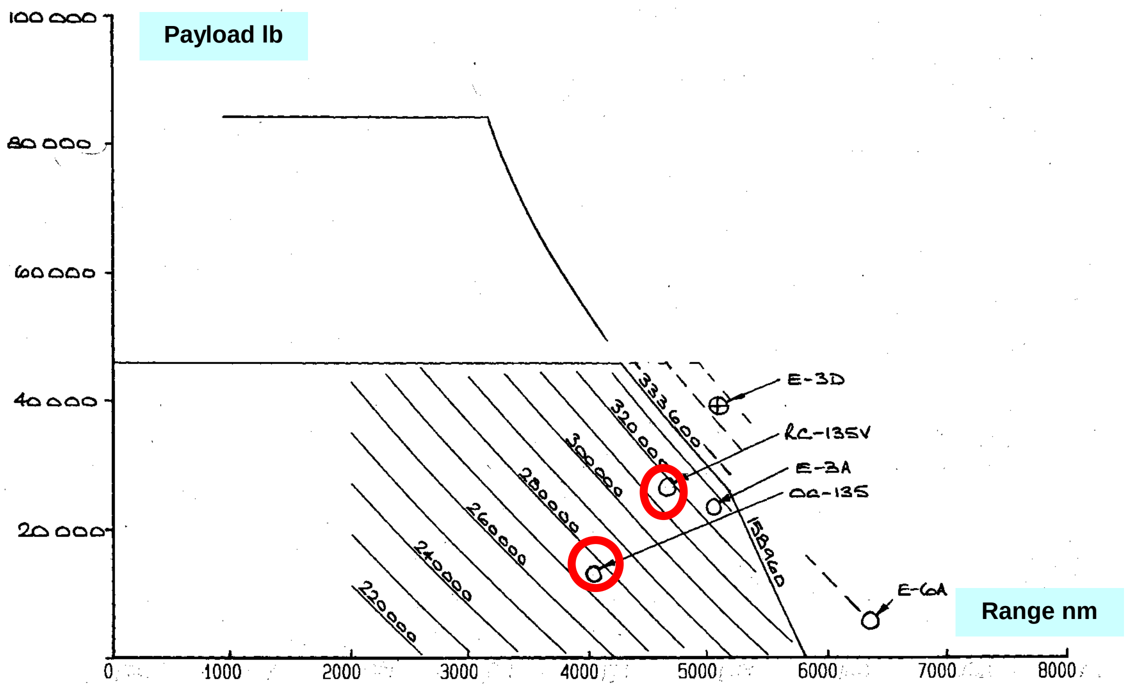


Fig. 6.2.1 B707-320C PAYLOAD RANGE DIAGRAM,
TYPICAL TOW – RANGE COORDINATES FOR SURVEILLANCE AIRCRAFT DERIVED FROM THE B707

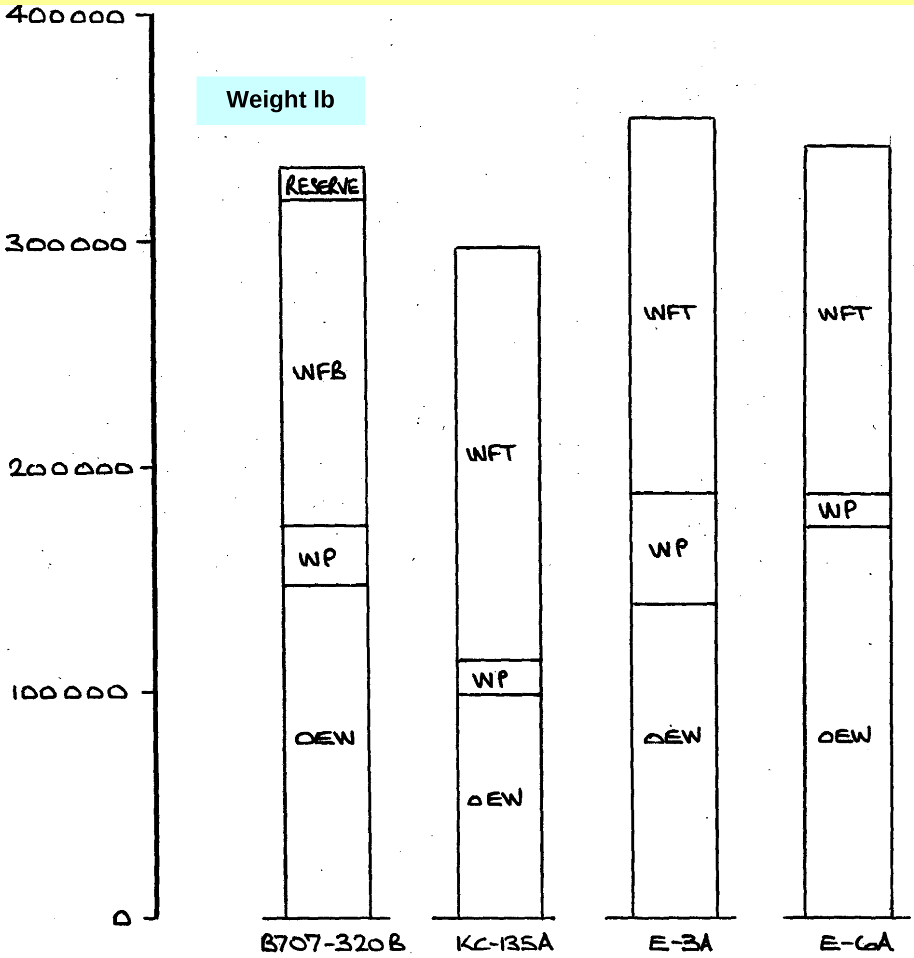


Fig. 6.2.2 TOTAL WEIGHT BREAKDOWN FOR SURVEILLANCE AIRCRAFT DERIVED FROM THE B707

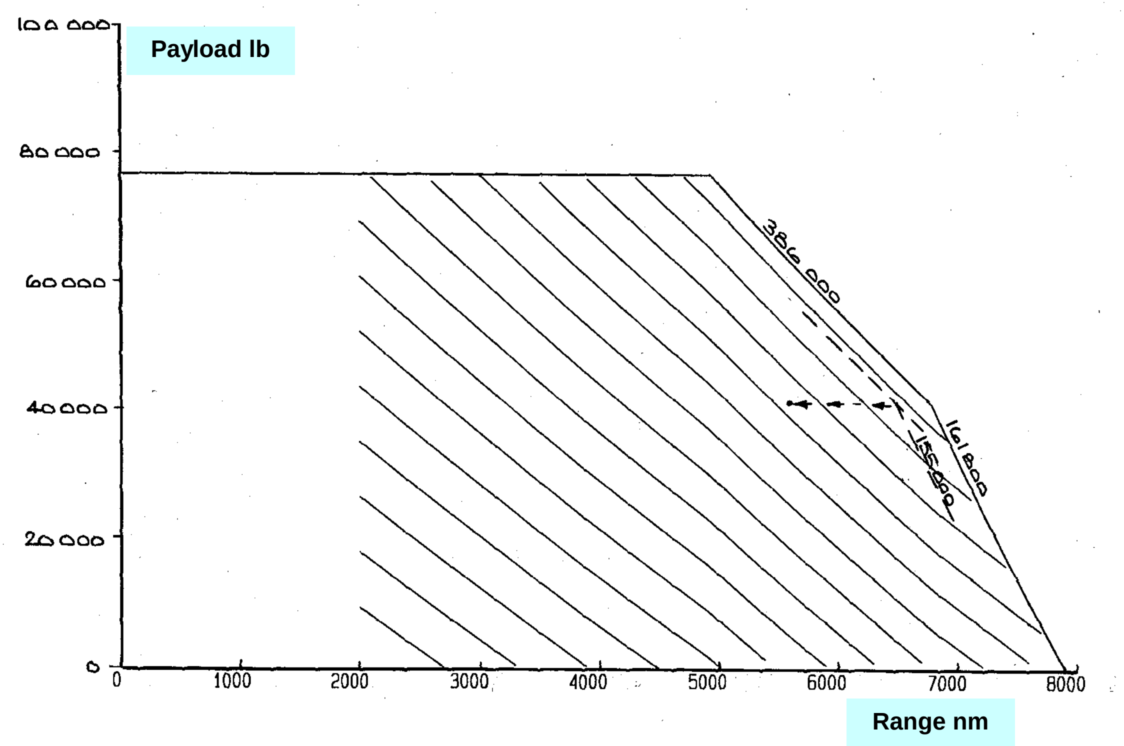


Fig. 6.5.1 B767-200 PAYLOAD RANGE DIAGRAM,
TYPICAL TOW – RANGE COORDINATES FOR SURVEILLANCE AIRCRAFT DERIVED FROM THE B767

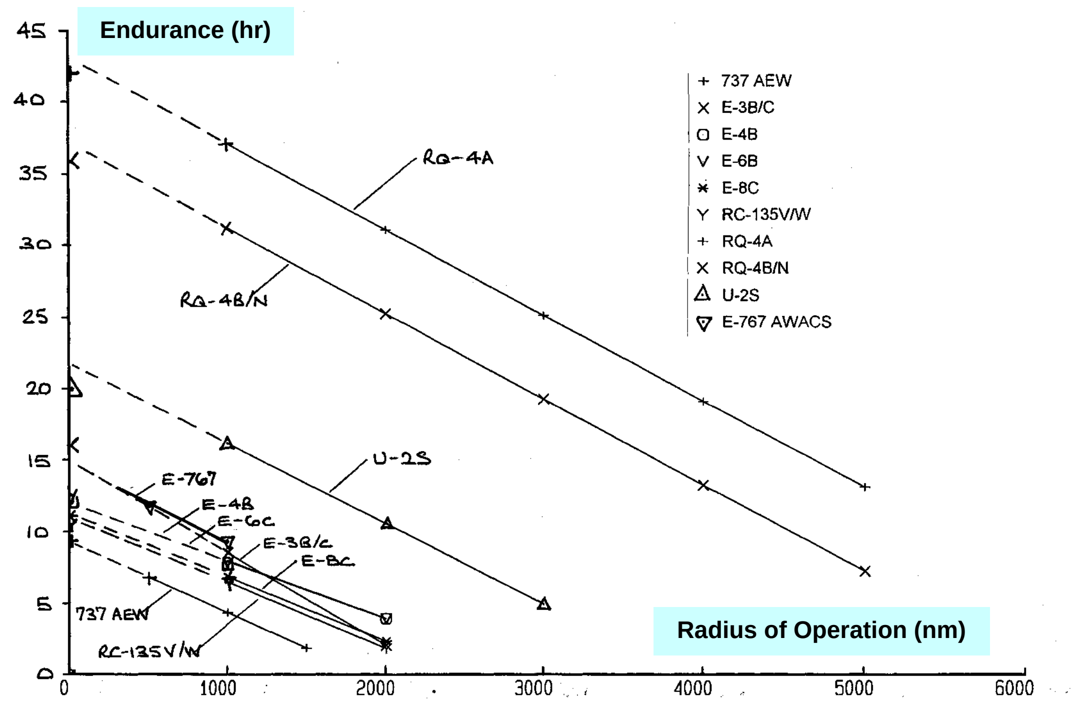


Fig. 6.11.1 ENDURANCE (hours on station) v OPERATIONAL RADIUS,
MANNED and UNMANNED SURVEILLANCE AIRCRAFT

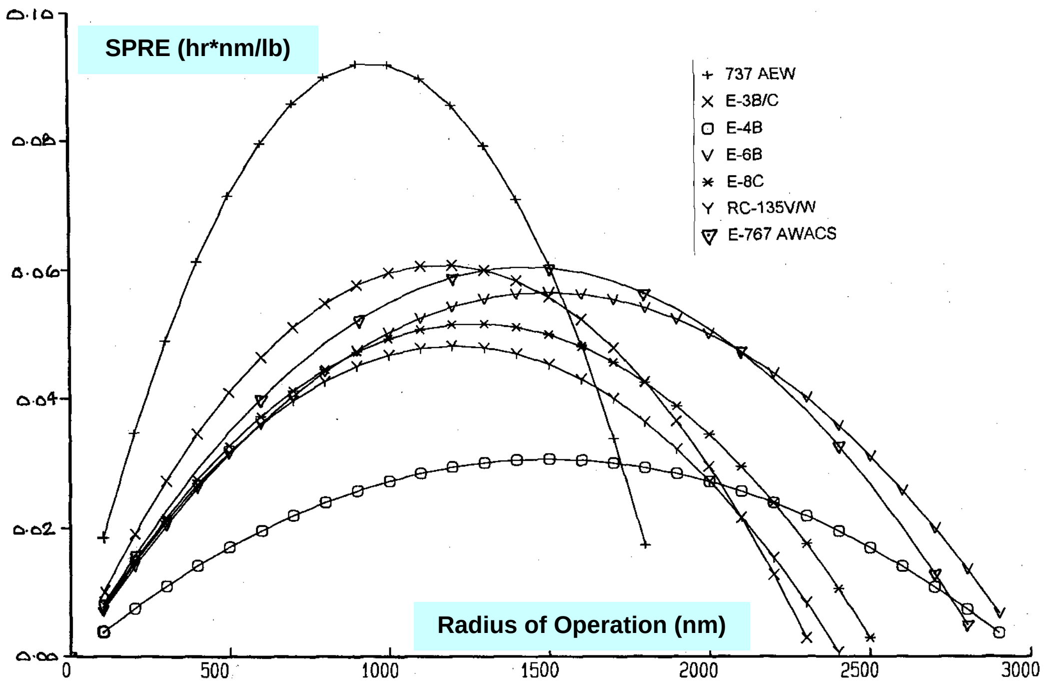


Fig. 6.11.2 SURVEILLANCE EFFICIENCY (SPRE) VARIATION WITH RADIUS OF OPERATION, LARGE, CONVENTIONAL AIRCRAFT

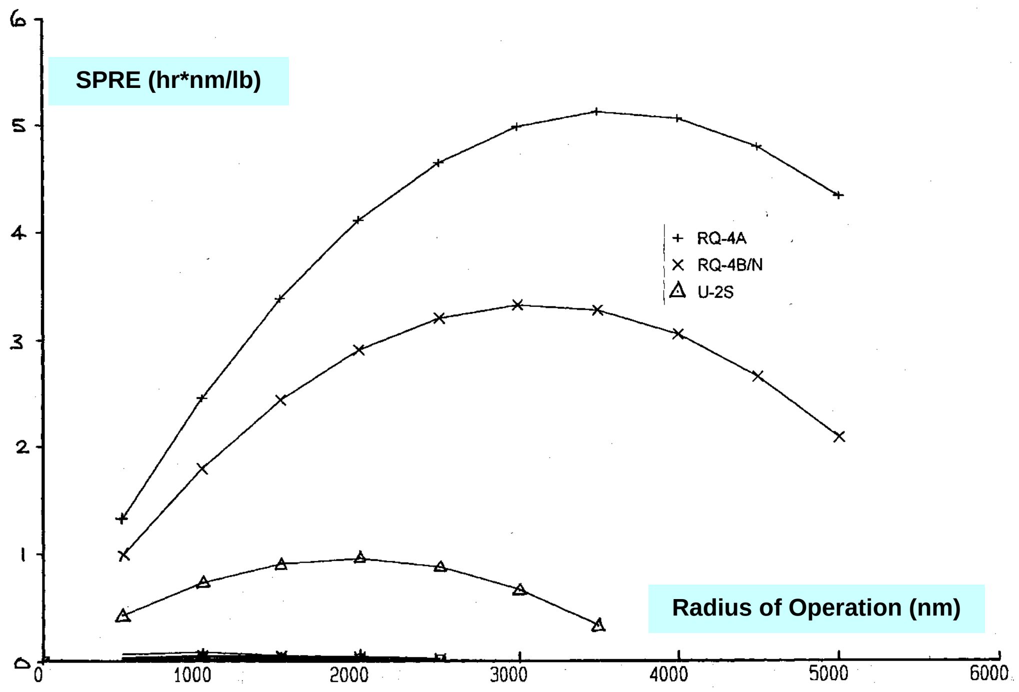


Fig. 6.11.3 SURVEILLANCE EFFICIENCY (SPRE) VARIATION WITH RADIUS OF OPERATION, U-2 and UNMANNED GLOBAL HAWK

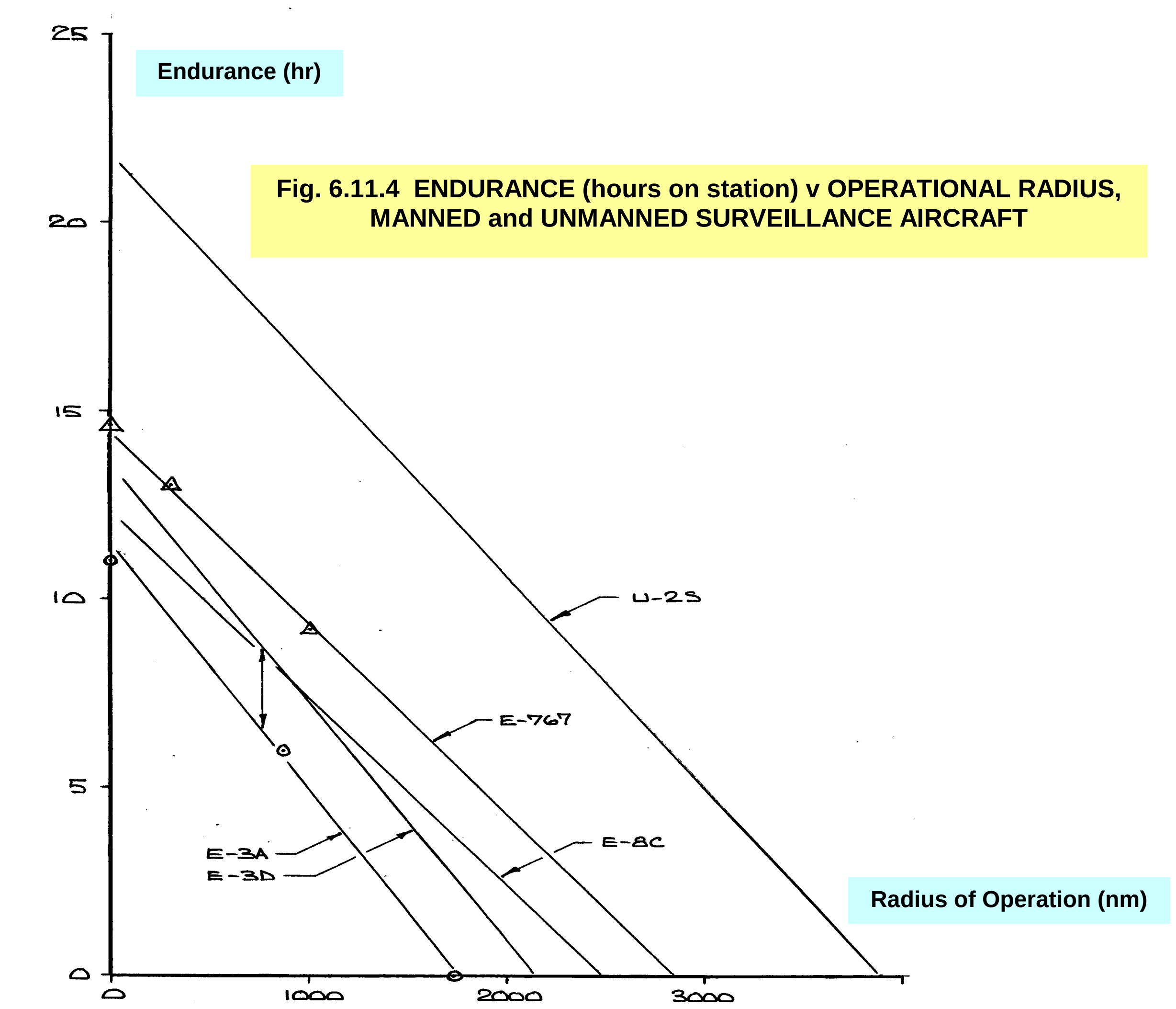


Fig. 6.11.4 ENDURANCE (hours on station) v OPERATIONAL RADIUS, MANNED and UNMANNED SURVEILLANCE AIRCRAFT

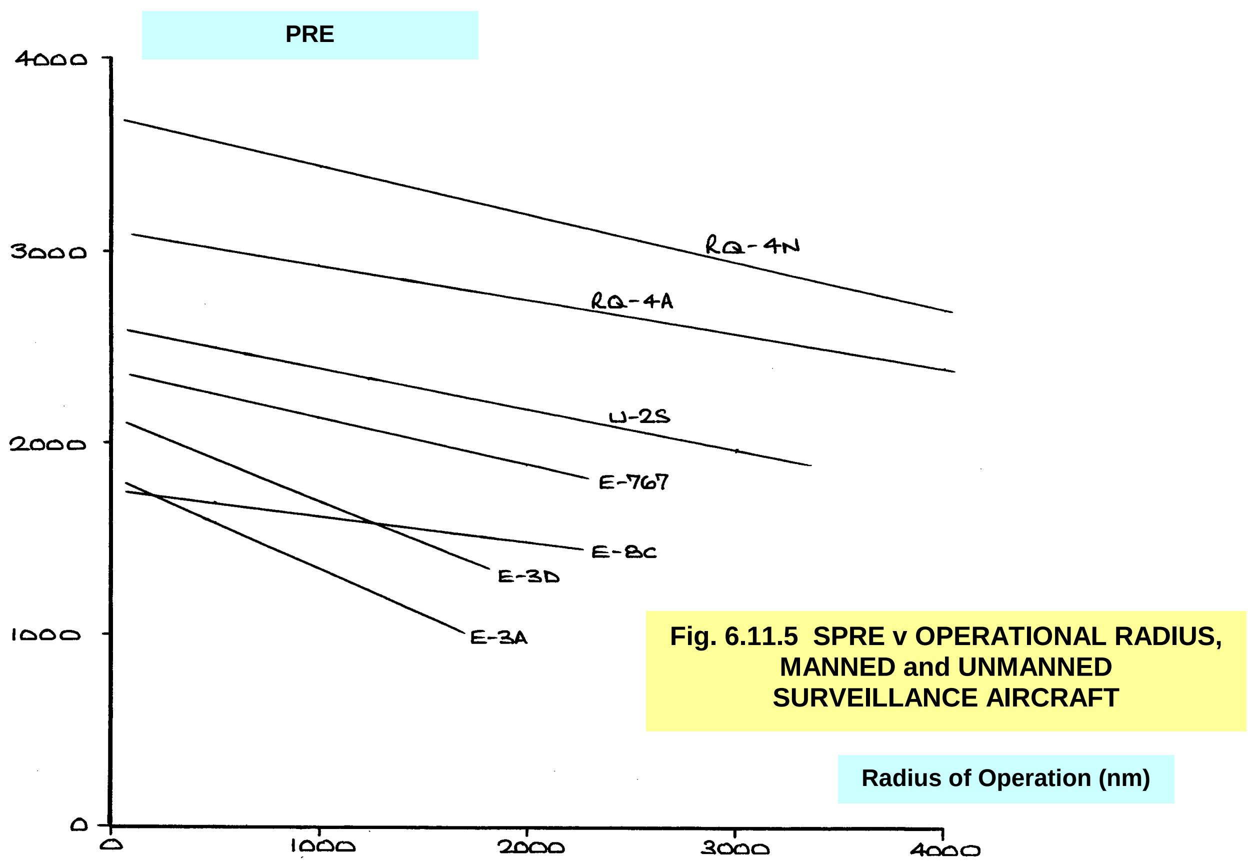


Fig. 6.11.5 SPRE v OPERATIONAL RADIUS, MANNED and UNMANNED SURVEILLANCE AIRCRAFT

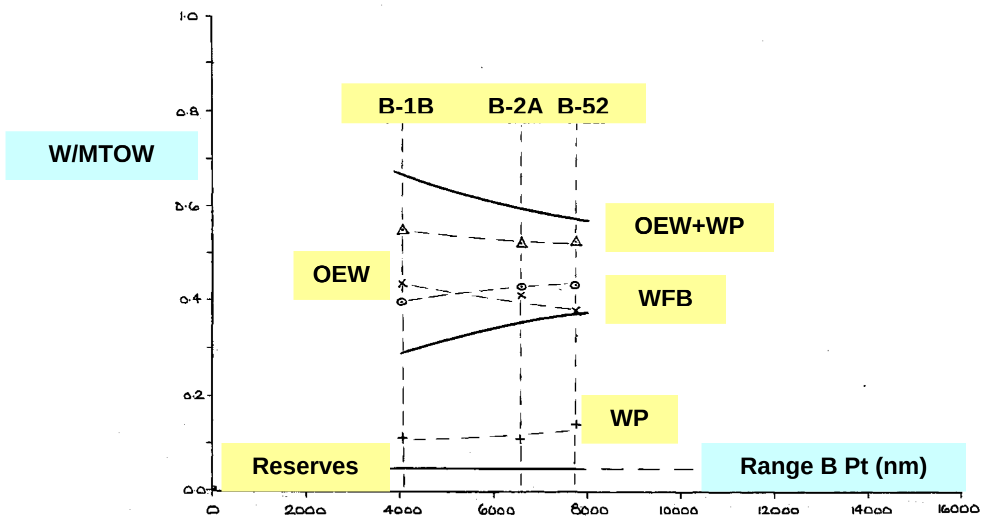


Fig. 7.1.1 BOMBER, WEIGHT RATIOS wrt MTOW v POINT B RANGE, CIVIL FREIGHTER JET AIRCRAFT TRENDS

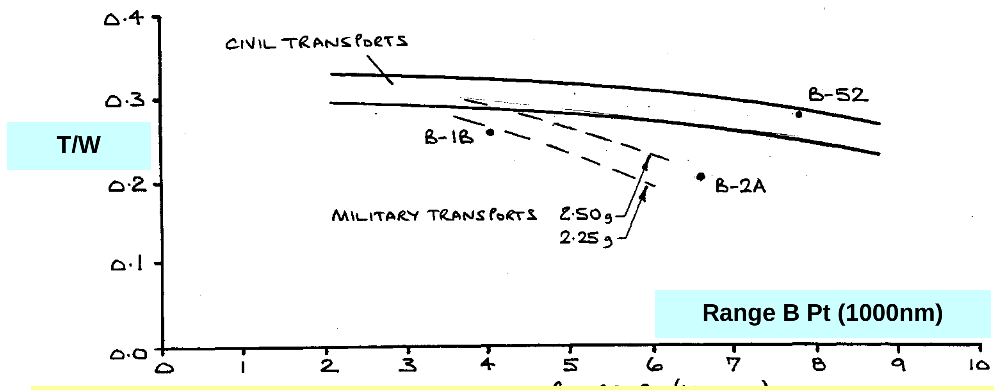


Fig. 7.1.2 BOMBER, T/W - B RANGE, CIVIL and MILITARY TRANSPORT TRENDS

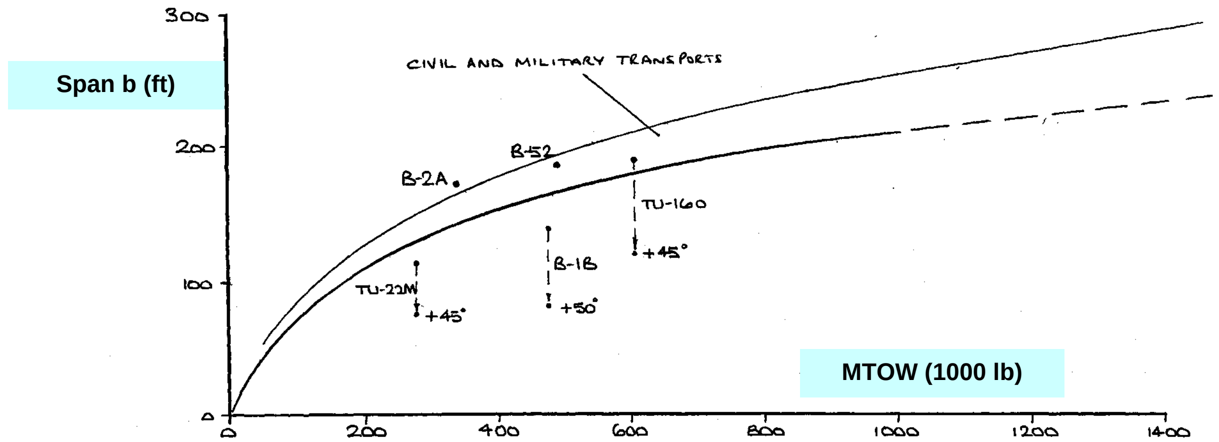


Fig. 7.1.3 BOMBER, SPAN (b ft) - MTOW, CIVIL and MILITARY TRANSPORT TRENDS

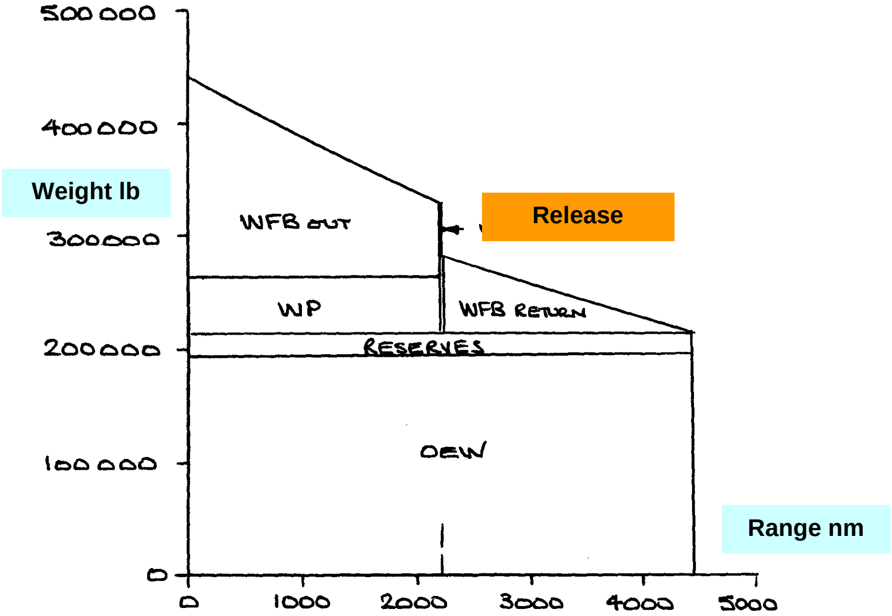


Fig. 7.2.1 B-1B, TOTAL WEIGHT VARIATION WITH RANGE AND WEAPON RELEASE

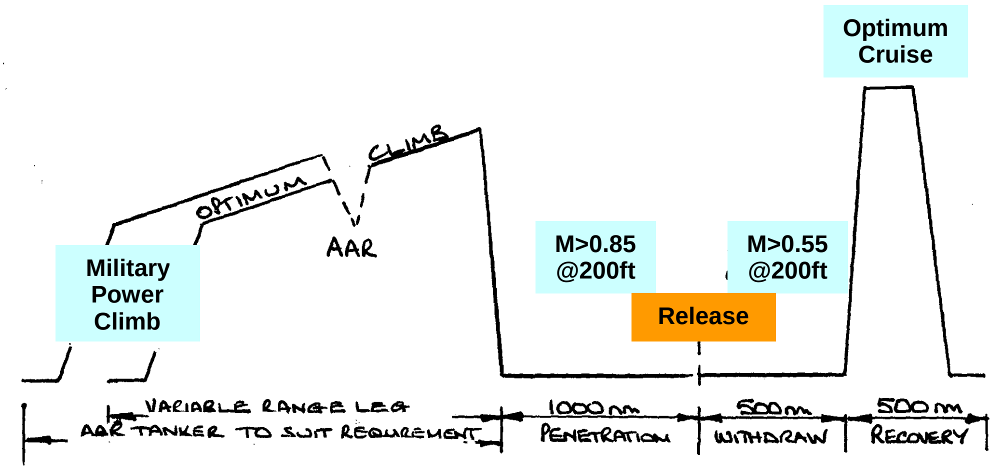


Fig. 7.2.2 B-1B, SCHEMATIC ILLUSTRATING TYPICAL SIOP MISSION

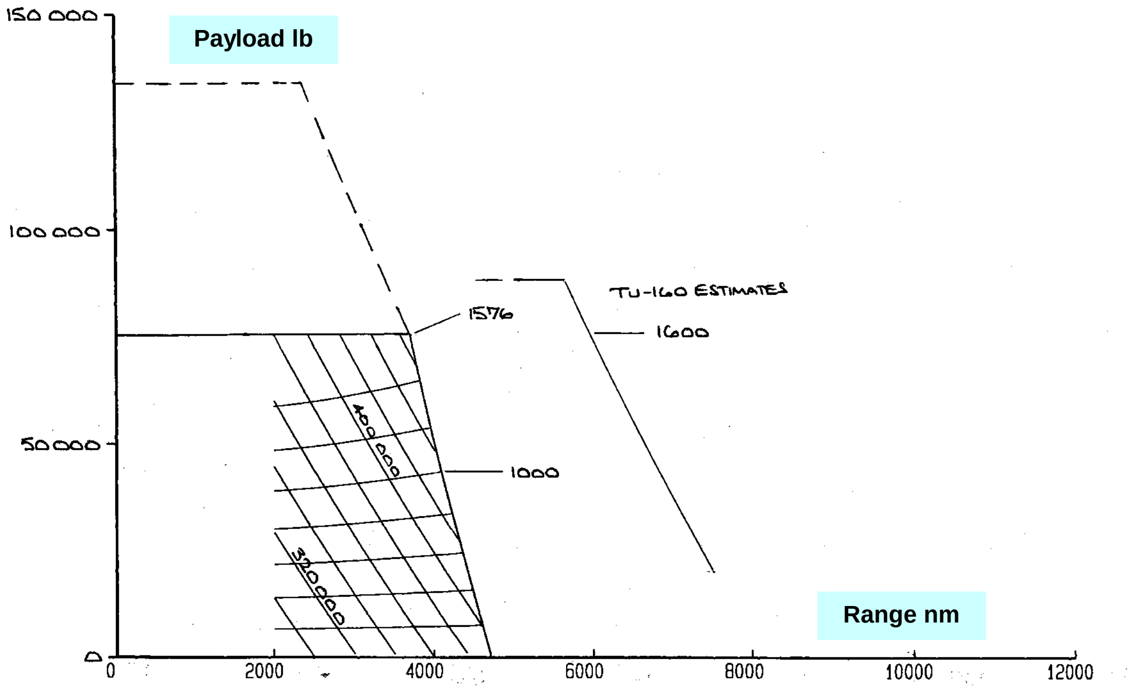


Fig. 7.2.3 B-1B, PAYLOAD - RANGE DIAGRAM (PAYLOAD RETAINED), ISO PRE LINES, ISO TOW LINES, TU-160 ESTIMATES INCLUDED

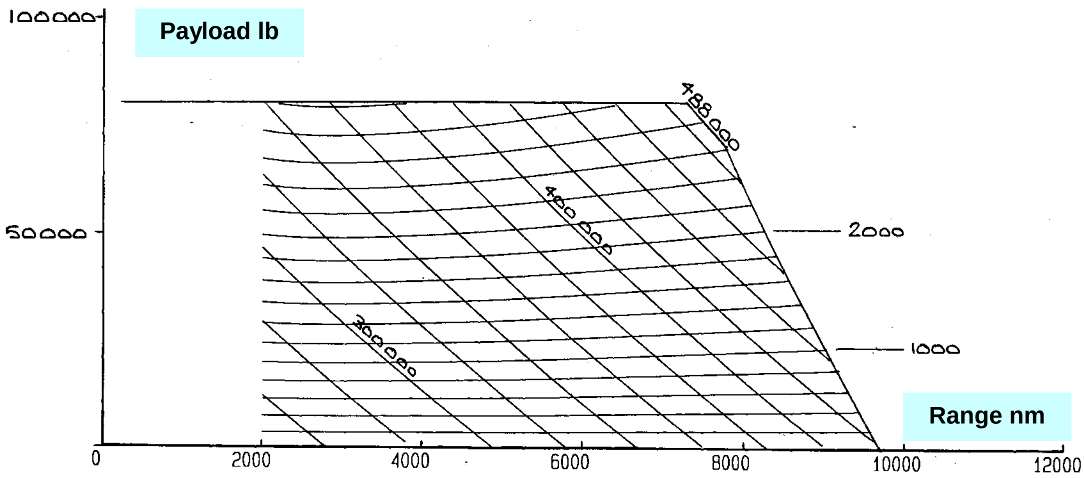


Fig. 7.3.1 B-52H, PAYLOAD - RANGE DIAGRAM (PAYLOAD RETAINED), ISO PRE LINES, ISO TOW LINES

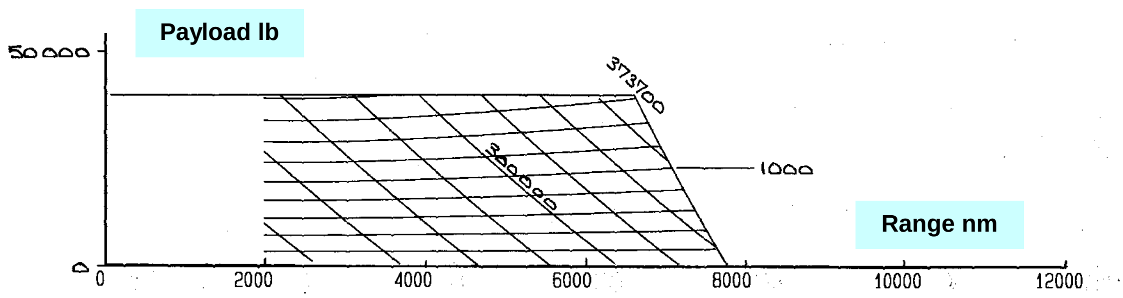


Fig. 7.4.1 B-2A, PAYLOAD - RANGE DIAGRAM (PAYLOAD RETAINED), ISO PRE LINES, ISO TOW LINES

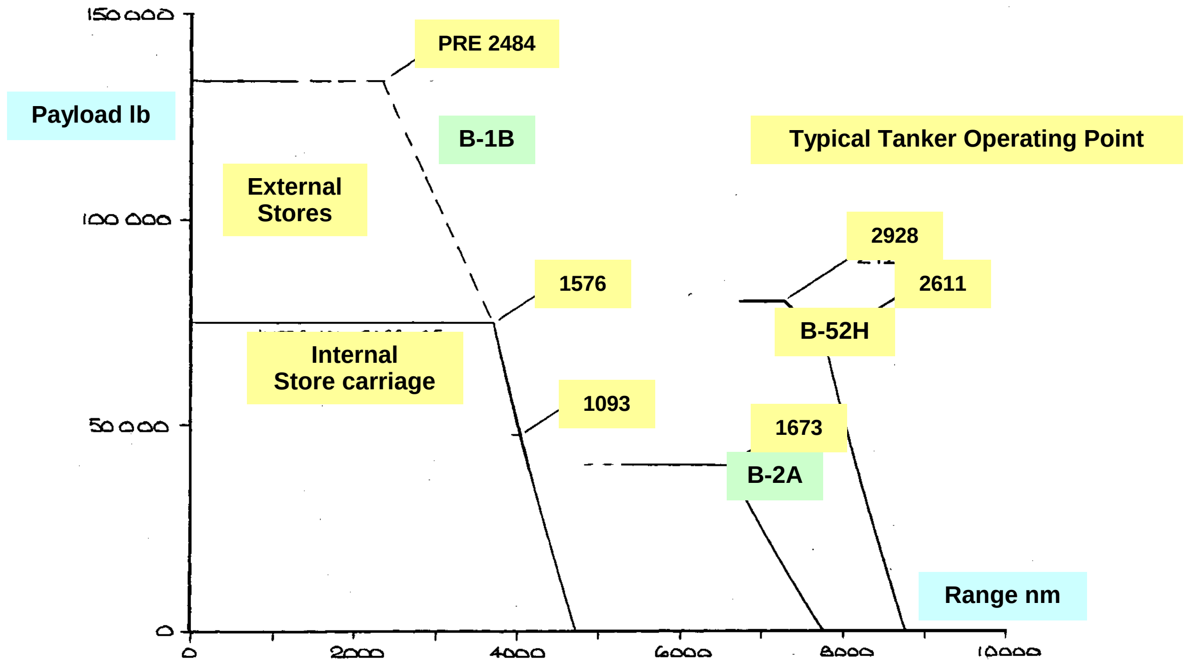


Fig. 7.5.1 BOMBER PAYLOAD (RETAINED) v RANGE DIAGRAM, B-1B, B-2A and B-52 COMPARED, PRE VALUES

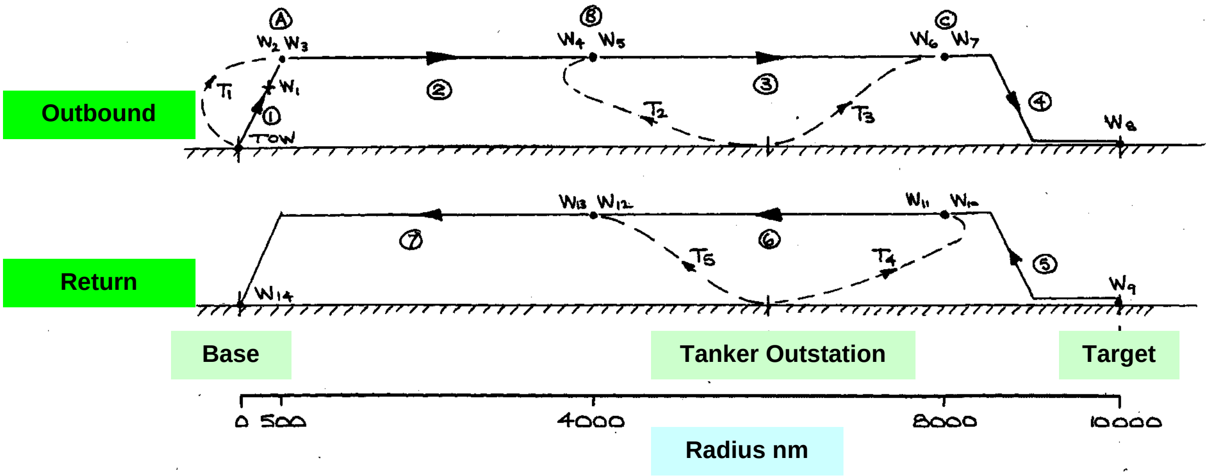


Fig. 7.5.2 MISSION SCENARIO, BOMBER WEIGHT (W1 to W14), TANKER OPERATIONS (T1 to T5)
TARGET 10,000 nm FROM BASE, TANKER OUTSTATION 6,000 nm FROM BASE

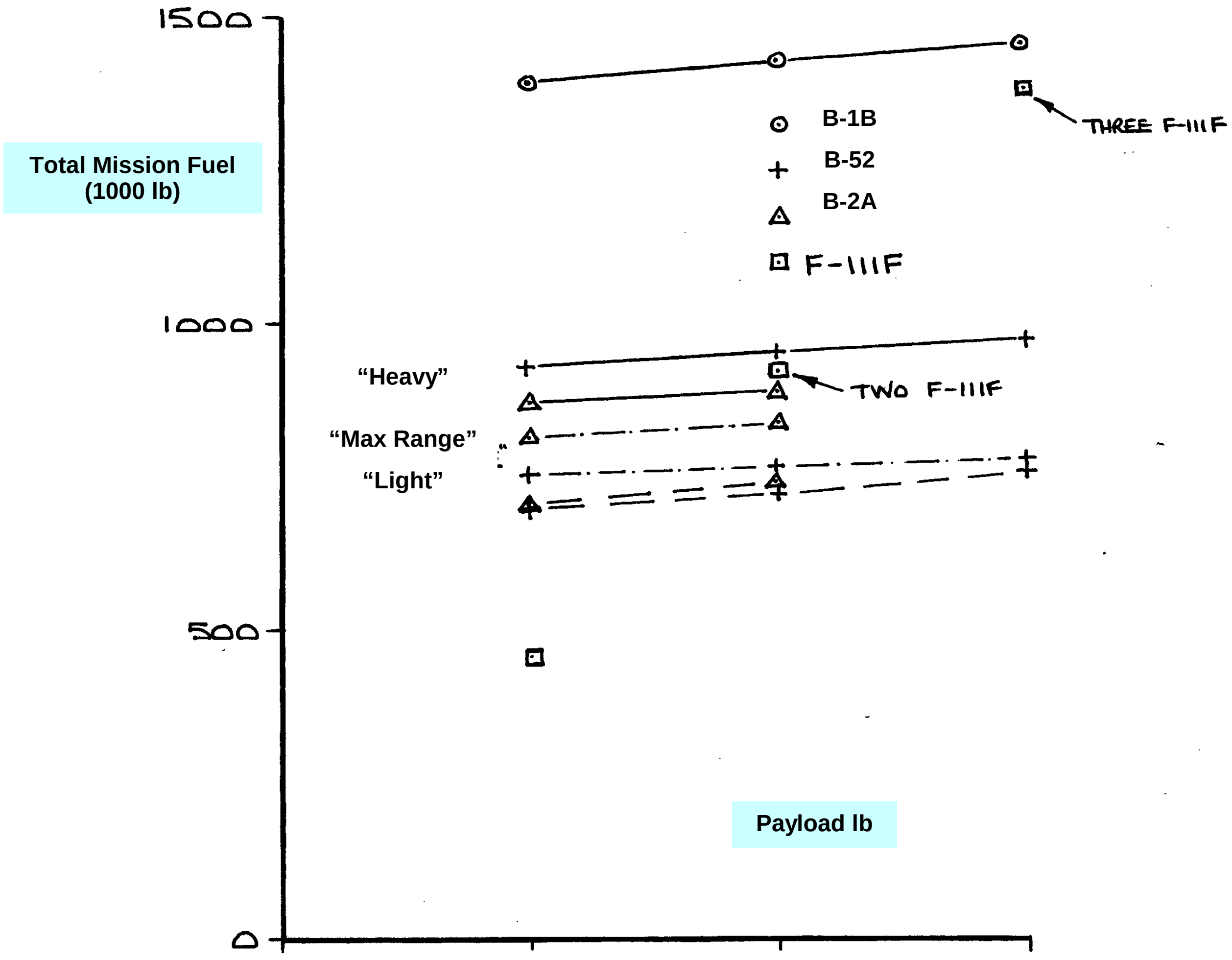


Fig. 7.5.3 TOTAL MISSION FUEL (BOMBER + TANKER) v
PAYLOAD DELIVERED
TARGET 10,000 nm FROM BASE, TANKER OUTSTATION 6,000 nm
FROM BASE
B-1B, B-2A and B-52 COMPARED

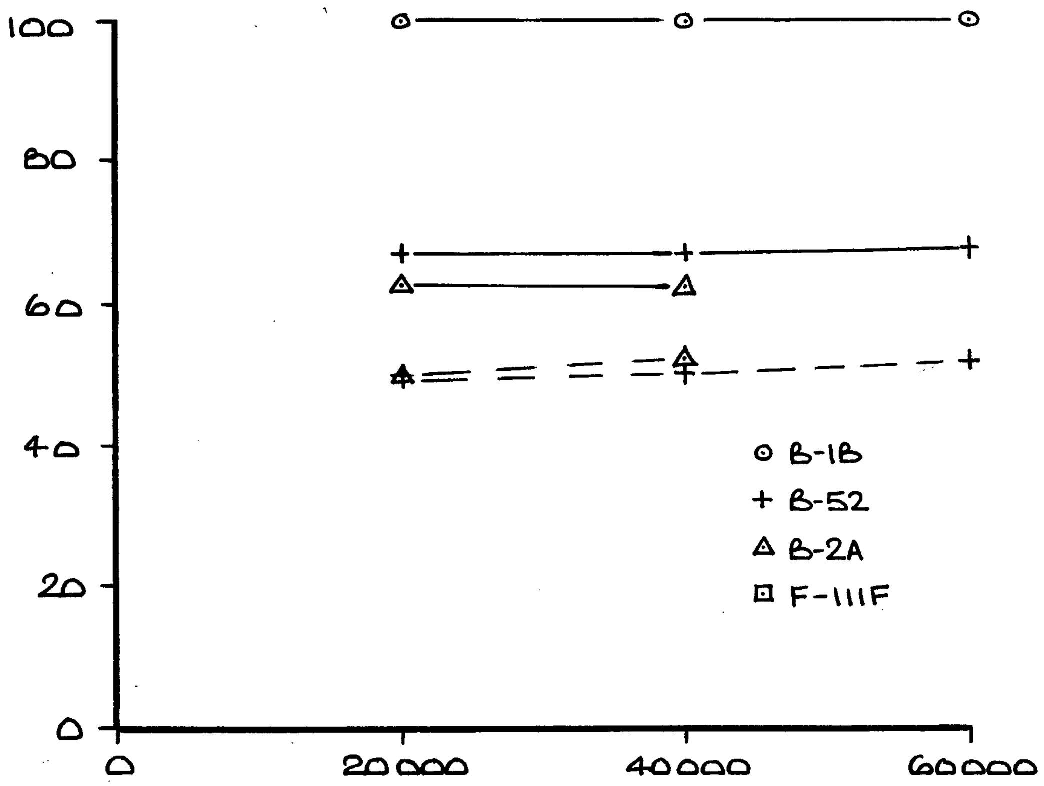


Fig. 7.5.4 MISSION FUEL PERCENTAGE BASED ON B-1B
TARGET 10,000 nm FROM BASE, TANKER OUTSTATION 6,000 nm FROM BASE
B-1B, B-2A and B-52 COMPARED, PRE VALUES

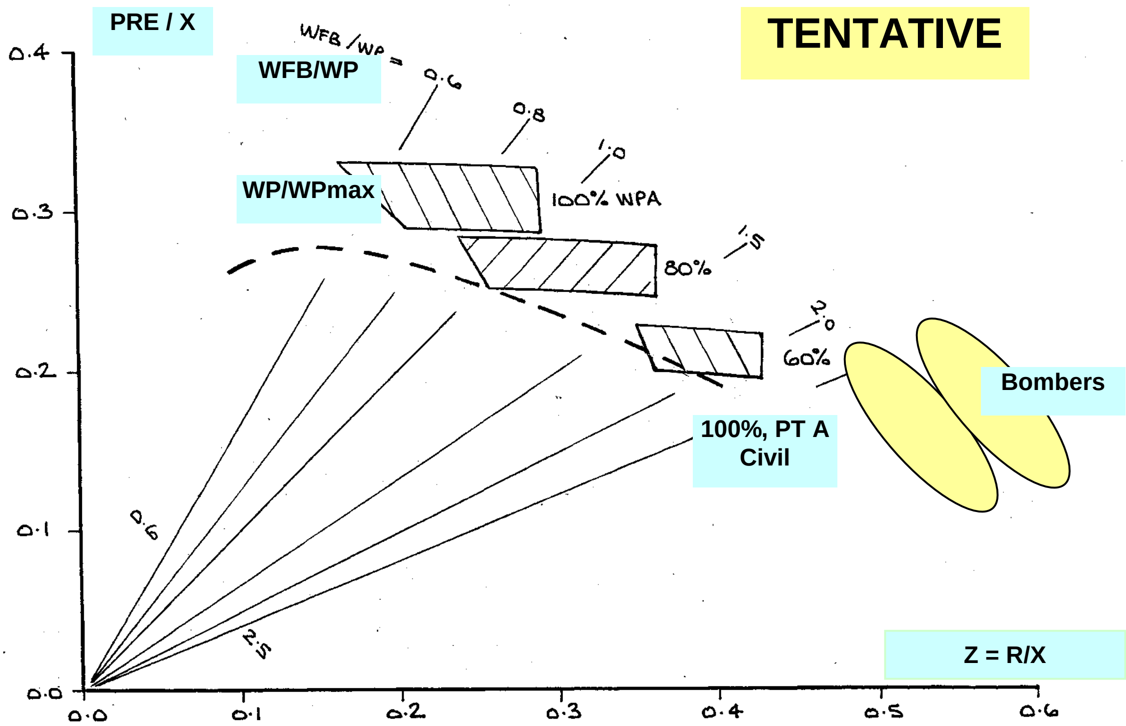


Fig. 7.5.5 PRE/X vs Z, BANDS FOR VARYING PAYLOAD FRACTION, FREIGHTER AIRCRAFT, CIVIL AIRCRAFT PT A TRENDS, CONSTANT WFB/WP (RADIAL LINES), BOMBERS ADDED